Transactions of the IRE Professional Group on ELECTRONIC COMPUTERS

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TABLE OF CONTENTS

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WESTERN ELECTRONIC SHOW AND CONVENTION
Long Beach, California - August 27-29, 1952

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Electronic Manufacturers' Association

Technical Sessions on Electronic Computers

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FOREWORD

This is the first issue of the Transactions of the IRE Professional Group on Electronic Computers. It contains the electronic computer papers presented at the Western Electronic Show and Convention in Long Beach, California, August 27-29, 1952, which was co-sponsored by the I. R. E. The work of arranging for the presentation and publication of these papers was done entirely by members of the Los Angeles Chapter of the Group.

Future issues of the Transactions are in preparation, and it is planned that they consist of papers individually submitted for publication as well as computer papers of special interest selected from those presented at conventions and meetings. All papers will be subject to review by the Board of Reviewers of the Professional Group. Papers should be submitted to J. H. Felker, Chairman of the Paper Study and Procurement Committee.

The Transactions of the P. G. E. C. are an I. R. E. publication devoted exclusively to electronic computers and allied subjects. It is hoped that this issue will be the start of a major publication in the field of digital and analog computer engineering, whereby technical papers of importance in this area can be made available to those who are most vitally interested.

A DIGITAL COMPUTER FOR AIRBORNE CONTROL SYSTEMS

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Introduction

A digital computer has been developed for use in airborne control systems. This application presents many problems. The computer must be small, light weight, and very reliable. It receives its input signals from instruments in the rest of the system. These signals are of the "analogue" continuous type and must be converted into the discrete electric signals used in the computer. The problems of analogue-digital conversion are problems in the measurement of the physical quantities that define the state of the system and in the transformation of the results of these measurements into digital signals. The digital numbers representing the input quantities are processed by the computer which performs in real time the computations corresponding to the mathematical representation of the control problem. The results of these calculations are numbers representing the signals used to control the system. These output numbers are converted into the analogue type signals used in the control operations.

The Computer

The computer is of the general purpose, serial, binary digital type. It has an arithmetic unit, a control unit, a magnetic drum memory unit, and an input-output unit. Although in a particular control system, there is a definite problem for the computer to solve; the simplest digital computer for a non-trivial problem has the characteristics of a general purpose computer; namely, it adds, subtracts, multiplies, divides, and transfers the numbers in its memory unit in response to a set of instructions specifying the sequence of arithmetic operations. Therefore, the computer proper is constructed as a general purpose computer. The special character of the application is reflected principally in the input-output unit.

The arithmetic unit performs the arithmetic operations of addition, subtraction, multiplication, and division. Serial operation in the binary number system is used since it leads to the simplest arithmetic unit. This unit consists of three one word circulating registers and a binary adder. Multiplication and division are scheduled automatically in terms of additions and subtractions.

The magnetic drum memory unit provides storage space for over 1500 nineteen digit words. Sixteen of these nineteen digits are available for number digits and one digit is a sign digit. The remaining two digits are used in switching operations. The density of the magnetic recording is approximately 100 binary digits per inch. The drum is four inches in diameter and rotates 8000 rpm, permitting the computing to take place at a rate of 160,000 binary digits per second. In order to reduce the access time, an eight word circulating register is provided.

The control unit reads orders from the memory unit and translates them into signals that direct the operation of the arithmetic unit. The code is

of the relative address[1] type and each order pertains to an operation on only one number. There are twenty-two orders in the code. These orders direct the arithmetic unit to carry out the arithmetic operations, transfer numbers to and from the arithmetic unit, detect negative numbers (to permit branch points in programming), and detect zero (to permit self-checking routines).

The switching circuits of the computer are composed of flip-flops and germanium diode gates. Their logical structure was designed with the aid of a computer algebra based on Boolean algebra.

The application of the computer to an airborne control system places severe restrictions on its size and weight as well as requiring it to operate under extreme environmental conditions. In order to achieve small size, subminiaturization techniques are employed throughout. Subminiature tubes, germanium crystal diodes, and etched circuit construction are all used. The requirement of operability under conditions of vibration and shock is met by a rugged mechanical design and the temperature requirements are met by circuits designed to operate even though the components---diodes, resistors, etc.--deteriorate appreciably from their rated values. Cooling is by forced air.

Accessibility of components and ease of check out and maintenance are obtained from a unitized type of construction. A standard flip-flop, which is used throughout the computer has been designed in the form of a plug-in unit. The diode networks associated with each flip-flop are also constructed as plug-in units. A photograph of the arithmetic unit and control unit, which have been packaged together, is presented in Figure 1. The magnetic drum memory unit, which includes the magnetic drum and associated circuitry, is shown in Figure 2.

Analogue-Digital Conversion

Analogue to digital input conversion devices have been developed for d.c. voltage, a.c. voltage, and shaft position inputs. Each of these input devices converts the analogue quantity into a time interval from which the digital number is obtained by counting timing pulses from the computer. This fact permits the input equipment to have a single counter which is switched in succession to each conversion device. Thus each input is sampled in succession. A similar set of conversion devices converts the digital numbers into voltages and shaft positions. The accuracy of the conversion appears to be limited principally by the problems in the accurate measurement of physical quantities and not by the digital output. Very precise measurements tend to require elaborate equipment.

In one application of this computer to a control system, there are ten analogue inputs and four analogue outputs. A bread-board construction of this input-output unit is shown in Figure 3. In this system the inputs and outputs are sampled at one-tenth second intervals. The complete computer system, including conversion devices, has approximately 250 tubes and 2000 germanium crystal diodes. Its volume is four cubic feet.

Acknowledgment

The development of this computer was a joint effort of more than thirty engineers, mathematicians, and physicists of the Hughes Aircraft Company Research and Development Laboratories.

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1. A. Zukin, "Automatic Program Control Utilizing A Variable Reference for Addressing," Proceedings of the Electronic Computer Symposium, April 30-May 1, 1952, at The University of California at Los Angeles.

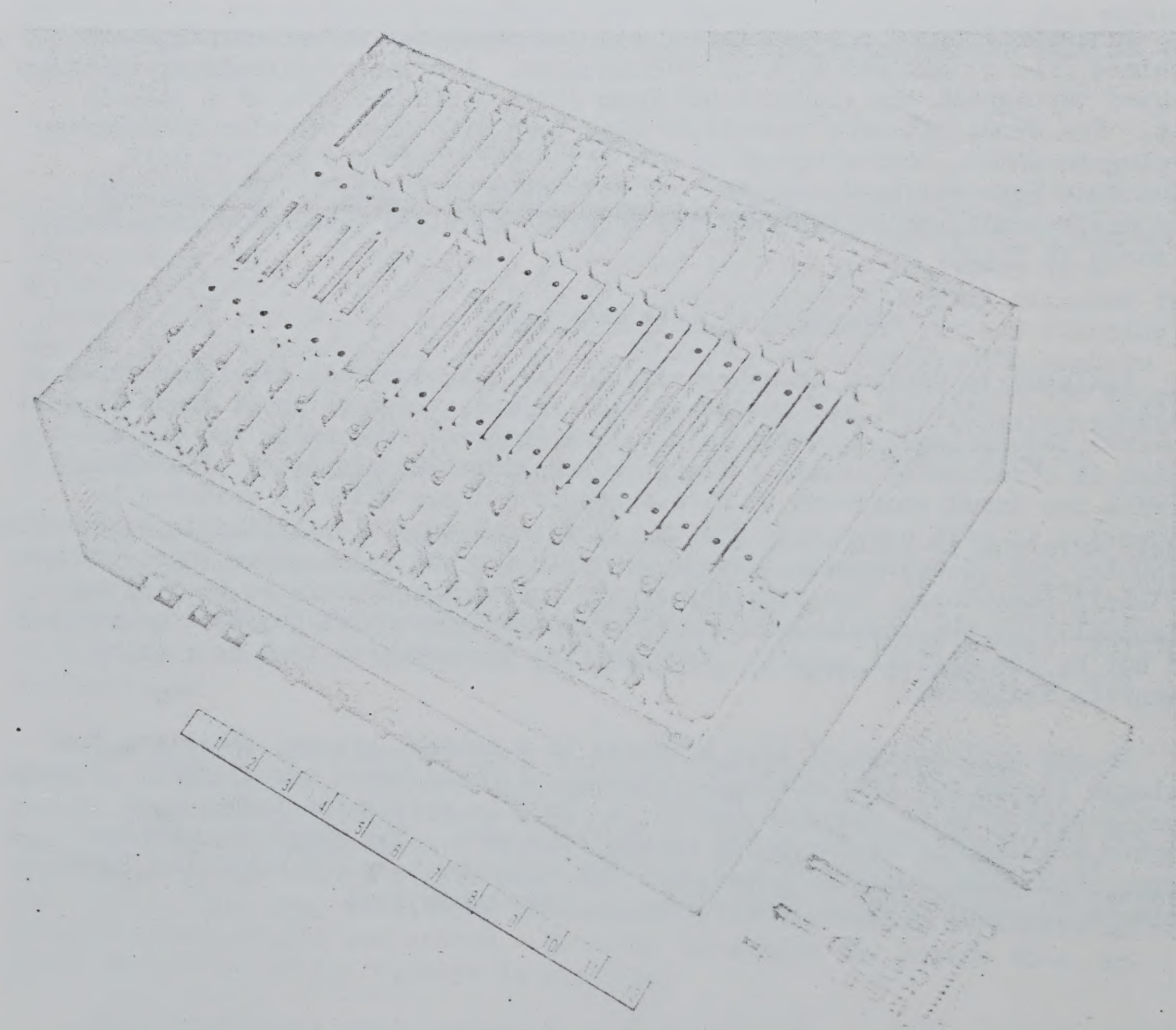

Figure 1 -- Arithmetic and Control Unit.

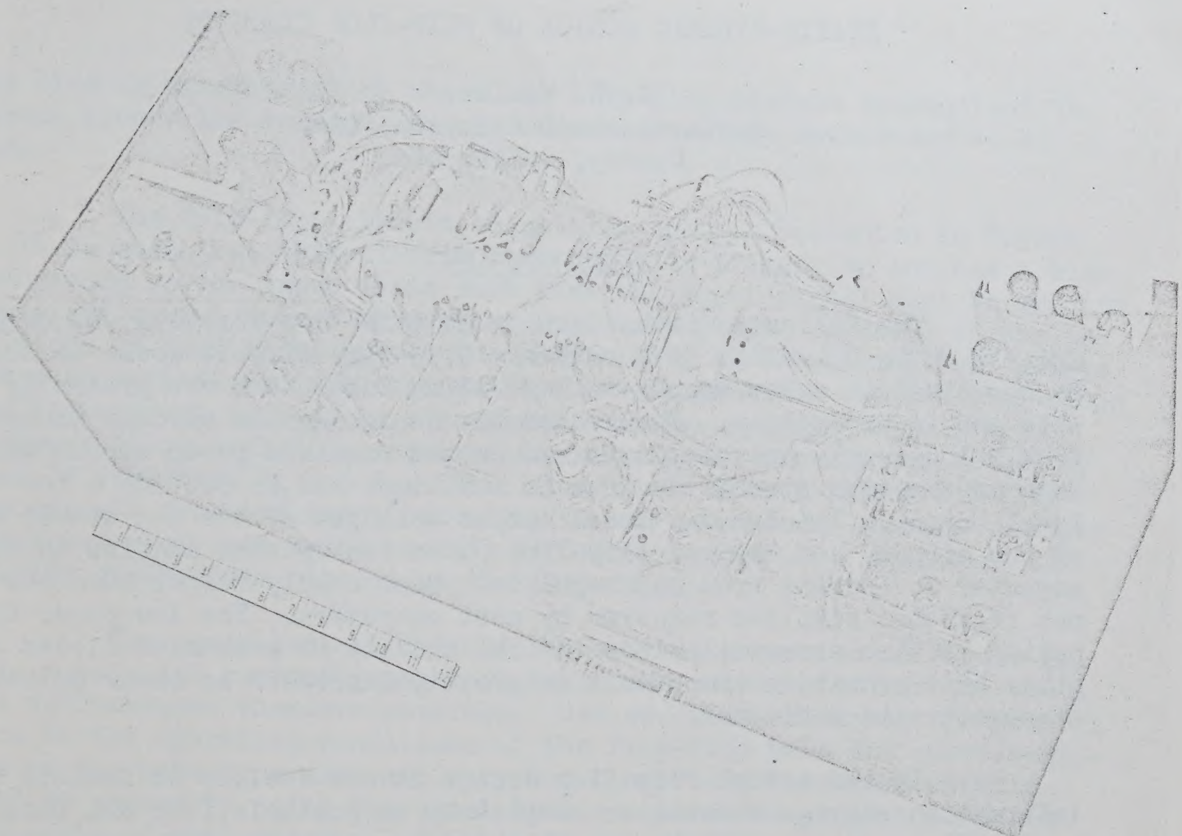

Figure 2 -- Magnetic Drum and Associated Circuitry.

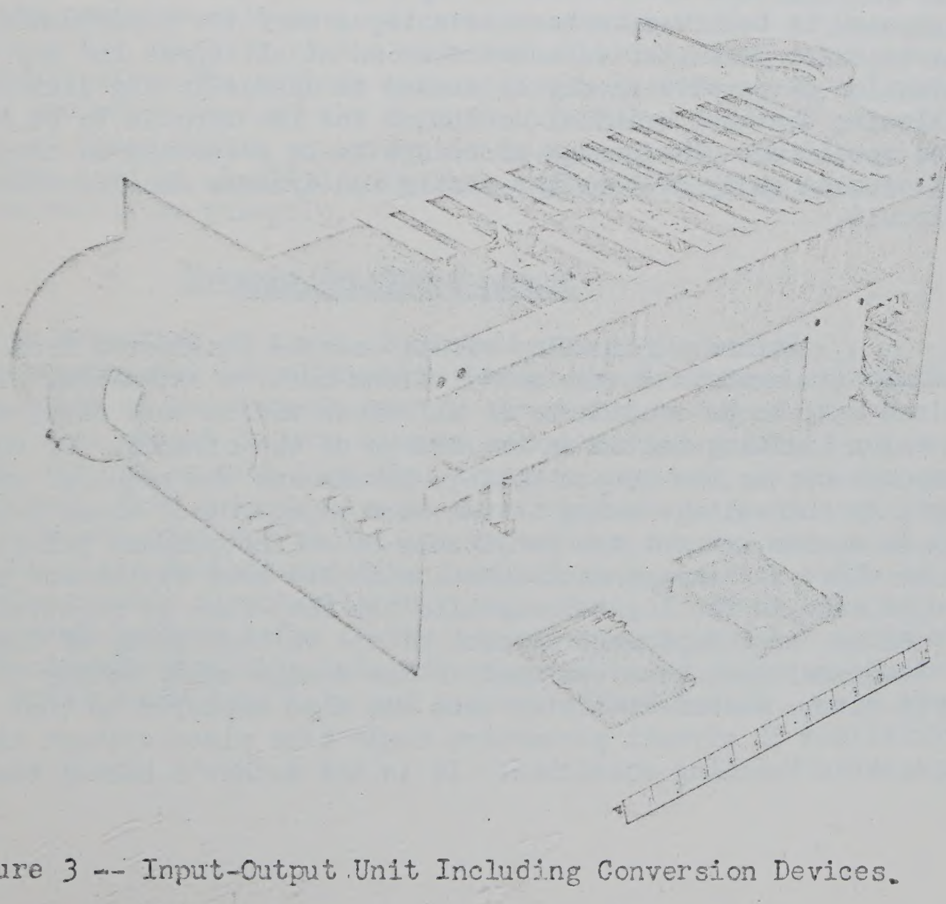

Figure 3 -- Input-Output Unit Including Conversion Devices.

STATIC-DYNAMIC DESIGN OF FLIP-FLOP CIRCUITS

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Introduction

The following investigation on flip-flop circuits was originally undertaken to determine if a reliable flip-flop circuit could be designed to operate from a low supply voltage using tubes that are presently available and in production. The reason for designing the circuit to operate from a low supply voltage is to reduce the required power consumption of such information storage devices to a minimum and to provide a low d-c level output. The low d-c level output voltages of the two stable states of the circuit and the low flip-flop power dissipation enables an entire computer to operate from one regulated power supply rather than the numerous regulated supplies required by most computers. The low power dissipation is also essential since the reliability of germanium diodes and other heat sensitive components is greatly increased as their operating temperature is decreased.

In the actual flip-flop design it was decided to isolate the information storage element as completely as possible from all outside load influences in order to permit the determination of the exact operating conditions of the circuit. Isolation of the storage element enables a complete analysis of the circuit to be made and permits the determination of all maximum allowable circuit parameter variations. The analytical approach is believed to have advantages over the experimental approach since exact parameter values are known at all times and any desired combination of parameters may be caused to change in any desired direction allowing the most critical condition for the circuit to be determined and specified. The design procedure to be presented is composed of an integrated study of both the static and dynamic considerations of the circuit.

Static Considerations

Before a flip-flop circuit can be considered from a dynamic standpoint certain static restrictions must be satisfied. These restrictions have to be considered at all times and in some cases actually are a major limiting factor on the design of the circuit. Of most general importance are the output voltage levels and the required voltage swing. Usually the voltage swing is the more important of these two items since it is chosen to meet the conditions of an independent function, as in this case where the independent function is the back resistance of the diodes to be used in the logical circuits the flip-flop is required to drive. To allow for independent control of the voltage swing of the circuit, cathode-resistor bias was used in the design study rather than fixed-grid bias. Cathode-resistor bias was also employed so that reasonable variations in circuit parameters could take place without the circuit operation becoming unistable. It is the author's belief that fixed-

grid bias is unsatisfactory where the flip-flop circuit is required to operate from a low voltage source and small voltage swings are to be used.

The flip-flop circuit as settled upon is presented in Figure 1. It is seen that this circuit uses negative triggering and has a bias arrangement on the input diode such that the input signal must be greater than a set amount before triggering will take place. Biasing of the input diode is used to eliminate the possibility of triggering from pulses formed by variations in output voltage levels from the various flip-flops when the circuit is used in a complete computer system. The minimum trigger voltage amplitude required to trigger the circuit may be set by means of resistors R_4 and R_5. The input diode also isolates the flip-flop circuit from the input circuitry as was previously stated. A major contribution of this input circuit isolating system is a reduction in capacity at the grid circuit of the flip-flop.

The equivalent circuit of Figure 1 is presented in Figure 2. It is noted that current generators have been substituted for the usual tube conductances wherever possible. Use was made of current generators since at the operating conditions of the flip-flop tube the characteristics of the tube type used are very non-linear and therefore nothing would be gained by using the usual static equivalent circuit composed completely of conductances. On the other hand the solution of the equations involved in the circuit using current generators is simple and rapid. An iterative process is used to determine the solution with a person acting as the error sensing element between the experimental tube curves and the computed voltages. As can be seen in Figure 2 the equations necessary for solution of the required static circuit voltages are extremely simple since the cathode circuit has been effectively isolated from the two resistive legs of the circuit by means of current generators. The main use of these static equations is in determining the values of tube parameters used in specifying whether a given flip-flop circuit is bi-stable, unistable or unstable.

Dynamic Considerations

Upon selection of a set of circuit values that meet all of the static requirements, the actual dynamic design may be initiated. The equivalent circuit of the dynamic case is presented in Figure 3. The cathode circuit is absent in this diagram since the resolution time of the flip-flop circuit is much less than the time constant of the cathode circuit. However, this cathode circuit time constant is small with respect to the time required for variations in voltage sources and parameter changes to take place so that negative feedback is present for all cases except when the circuit is actually changing state. In the equivalent circuit the primed letters refer to the lesser conducting tube and the branch of the circuit that this tube effects; the non-primed letters refer to the fully conducting tube and its associated branch of the circuit.

Since a flip-flop circuit is nothing more than a circuit with two stable states and a method by which it may be changed from one of these states to the other, we are mainly interested in two items in designing such a circuit. Thesé two items are:

1. How stable is the circuit with respect to external and internal influences other than that of the trigger input?

2. How much time is required for the circuit to change from one stable state to the other stable state when such a change is initiated?

Although both of these items are of importance the first one is more difficult to predict and usually the more important since the second item is more of a design limitation than a design consideration. The dynamic design discussed will deal only with the stability of the circuit.

Stability Determination

Naturally the most stable flip-flop circuit is one that is directly coupled to the input circuit and is continually presented with information telling if of its desired state. However, this type of circuit is really nothing more than a power amplifier that isolates the input system from the load. It is evident that this direct-coupled circuit cannot be used in a majority of cases and that some type of self-stable circuit must be used where input information is present only when a change in the circuit's state is desired. This type of circuit is inherently oscillatory during the change from one state to the other state. Therefore, we are presented with the problem of designing a circuit which can be made oscillatory at the will of the input information. Since we are not actually concerned with the process the circuit goes through during the switching state, it is believed that Routh's criteria for the determination of the stability of the circuit is best suited for this case.

Use of Routh's Criteria for Determining Stability

Expansion of the fourth order determinant formed by the coefficients of the four unknown voltages of the dynamic circuit equations results in a fourth order polynomial in p. By use of Routh's criteria we may determine the necessary conditions for a fourth order polynomial to be a Hurwitz polynomial or, in other words, determine the conditions that the circuit parameters must meet to make the circuit stable. The criteria for determining if such a polynomial is a Hurwitz polynomial is presented in Figure 4. If the conditions of Figure 4 are met the circuit may be concluded to be stable for the particular values of circuit parameters used. As can be seen in Figure 5, the coefficients of this fourth order polynomial are by no means simple since gm, gm', g_g, g_g', u, u', S_g, and S_g' are all dependent variables. Fortunately all of these dependent variables are functions of either gm or gm', which are in turn functions of the other circuit parameters and the characteristics of the tube being used in the circuit. Since it is possible to specify the

most critical values of g_L and g_L', which are the grid to cathode conductances of the two cathode followers associated with the circuit, and all other dependent variables are functions of gm or gm', we are dealing with a problem containing only two variables. This stability problem is therefore suited for solution by means of a digital differential analyzer. Since the factors S_g' and g_g' are negligibly small for most considerations, the more practical method of solution is to make gm the independent variable and compute gm' so as to give the boundary between stable and unstable operation. In the particular case with which the investigation was first concerned the factor u' was assumed a linear function of gm'. This assumption was possible since for the operating conditions where u' was not a linear function of gm' the plate conductance of the lesser conducting tube was negligible with respect to the term $g_1' + g_2' + g_L'$. In fact negligible error was introduced if u' was assumed a constant over the range to be investigated. It was therefore simple to compute gm' for any given gm since gm' appears only as a first order term in a_0, a_1, a_2, and a_3 and does not appear in a_4. The resulting equations for determining stability have $(gm')^3$ as the highest order term and a third order equation is presented for solution. The roots satisfying the conditions of Figure 4 can therefore be found by the trigonometric method of solution of the cubic equation. However, the problem was actually solved by means of a digital differential analyzer. The coding of the differential analyzer to solve such a problem is presented in Figure 6. It should be stated that in this case u and u' were assumed to be constants and g_g, g_g', S_g, S_g', g_L, and g_L' were zero because the design was such that no grid current was required for either the flip-flop tube or the cathode-follower tube. The solution was accomplished by generating gm' as the independent variable and determining gm such that the conditions specified by Routh's criteria are met.

The stability plot for the above case is presented in Figure 7. It is noticed that this plot contains only four curves where Routh's criteria indicated a total of six curves. This is because two of the curves occur in the negative gm region and are of no value in the stability analysis. Actually only one of the four curves of the stability plot is of interest in the determination of circuit stability and this is the curve that results in the lowest value of gm for any given value of gm'. The circuit is stable if its operation results in the region below or to the left of this stability boundary and is unstable if its operation is in the region above or to the right of the boundary. To decide if and under what conditions a circuit becomes unstable and consequently changes state, it is only necessary to determine the gm and gm' of the tube in the circuit by means of the static equations and the tube characteristics of that particular tube. These values of gm and gm' will indicate the dynamic operating point on the stability plot of Figure 7. The circuit is bistable if the dynamic operating points of both states of the flip-flop circuit are in the stable region. The circuit is unistable if one operating point is in the stable region and one point is in the unstable region. The circuit is oscillatory if both dynamic operating points are in the unstable region.

Allowable Parameter Variations

In investigating the problem of determining the maximum allowable resistance variations permissible for a given flip-flop circuit it was found that the effective change in gm and gm' caused by the varying resistances has a much greater effect upon stability than the actual resistance change does. Since the dynamic stability plot does not have gm or gm' as a fixed parameter it is seen that only one stability plot is necessary for any given relation among the parameters of a particular tube. At most two stability plots would be necessary. One plot for the average tube parameter relation is necessary for the original investigation and one stability plot for the most critical case that is expected from a statistical analysis of a number of tubes of the type that is to be used in the circuit is needed. The most unfavorable condition for circuit resistance variations is:

R_1 decreasing in value	R_1' increasing in value
R_2 decreasing in value	R_2' increasing in value
R_3 increasing in value	R_3' decreasing in value

This is as expected since it can be seen that this condition caused the gm and gm', used to determine if the circuit is stable, to decrease and increase respectively, in turn causing the dynamic operating point of the circuit to be displaced towards the boundary line between stability and instability. However, the probability of such a variation in parameters occurring is very small and the actual case of one resistor failing completely is believed more probable. The maximum allowable percentage that these resistors may change in the most critical directions is important in that it does indicate the percent tolerance resistors that should be used in the circuit. Also it is usually a good indication of just how stable the circuit actually is. The maximum allowable simultaneous change in the most critical directions of the resistance values of the circuit for which the stability plot of Figure 7 was made is 4%. The permissible variation in resistance values for the circuit being used for computer work is much greater.

Of interest, and probably the most important information with regard to the stability of the circuit, is the variation in tube characteristics that a particular circuit will allow and still operate correctly. With this in mind, it was decided that it might be of interest to indicate the amount of allowable tube parameter variations which circuits have been successfully designed to handle. With the circuit for which the stability plot of Figure 7 was shown, the maximum possible variation in gm was found to be -60%, both analytically and experimentally, from the mean value. The allowable variation in gm of the tube in the circuit presently being used for digital computer work is -85% from the mean of a number of tubes for which tube characteristics have been taken. To demonstrate the effect of an unbalanced tube on the latter mentioned circuit, a tube with a transconductance of 3200 micro mhos on one side

and 500 micro mhos on the other side was found to work very satisfactorily in the circuit. In fact, the only noticeable difference in its operational characteristics from that of a well balanced tube in the circuit was a slight increase in required trigger voltage necessary to trigger from the most stable state to the least stable state. There was no noticeable change in other dynamic conditions and negligible change in static conditions. The mean value for 40 of this type tube at the same operating conditions as the above test tube gave a transconductance of 2000 micro mhos. It is also of interest to note that this circuit will operate correctly from a supply voltage of twenty to over two hundred volts.

General Design Information

As might be expected, general information was gained from this investigation that is helpful in designing flip-flop circuits using a low supply voltage. In concluding this paper, it was believed beneficial to list some of the more important items:

1. A tube type should be chosen that exhibits a large slope in the gm versus grid voltage curve so that stability can be assured for small plate and grid voltage swings.

2. Selection of a tube with a low value of grid current for a given gm is helpful.

3. The circuit should be designed so that the maximum transconductance is present at the operating point of the conducting tube. Designing for maximum transconductance usually results in grid current which must be taken into consideration in the actual circuit design.

4. Cathode-resistor bias should be used to allow for circuit and tube parameter variations. The time constant of the cathode circuit of the flip-flop should be small with respect to the anticipated time required for variations in supply voltages and circuit parameters to take place. The time constant of the cathode circuit should be large with respect to the resolution time of the circuit if easy triggering is required.

5. Isolation of the grid circuits and plate circuits of the flip-flop from all capacitive loads and low impedance sources is very important.

6. The higher the transconductance of the fully conducting tube, the more stable the circuit with respect to internal and external influences other than the triggering pulse.

7. In deciding upon a cathode-follower tube type, the larger the values of plate current and transconductance per given amount of grid current, the better the tube for this purpose.

8. The value of cross over capacitors is not exceptionally critical. However, the optimum size of these capacitors depends upon the magnitude of the various wiring and tube element capacitance.

Acknowledgements

Grateful acknowledgement is extended to R. A. Seymour, R. A. Stafford and L. L. Kilpatrick for their assistance in this undertaking.

Addendum

The quantities used in Figure 5 are as follows:

$$a = q_1 + q_2 + q_p + q_L$$

$$b = q_1' + q_2' + q_p' + q_L'$$

$$f = q_2 + q_3 + q_g'$$

$$f' = q_2' + q_3' + q_g$$

$$k = c_1 + c_2 + c_4$$

$$k' = c_1' + c_2' + c_4'$$

$$l = c_1' + c_2 + c_3$$

$$l' = c_1 + c_2' + c_3'$$

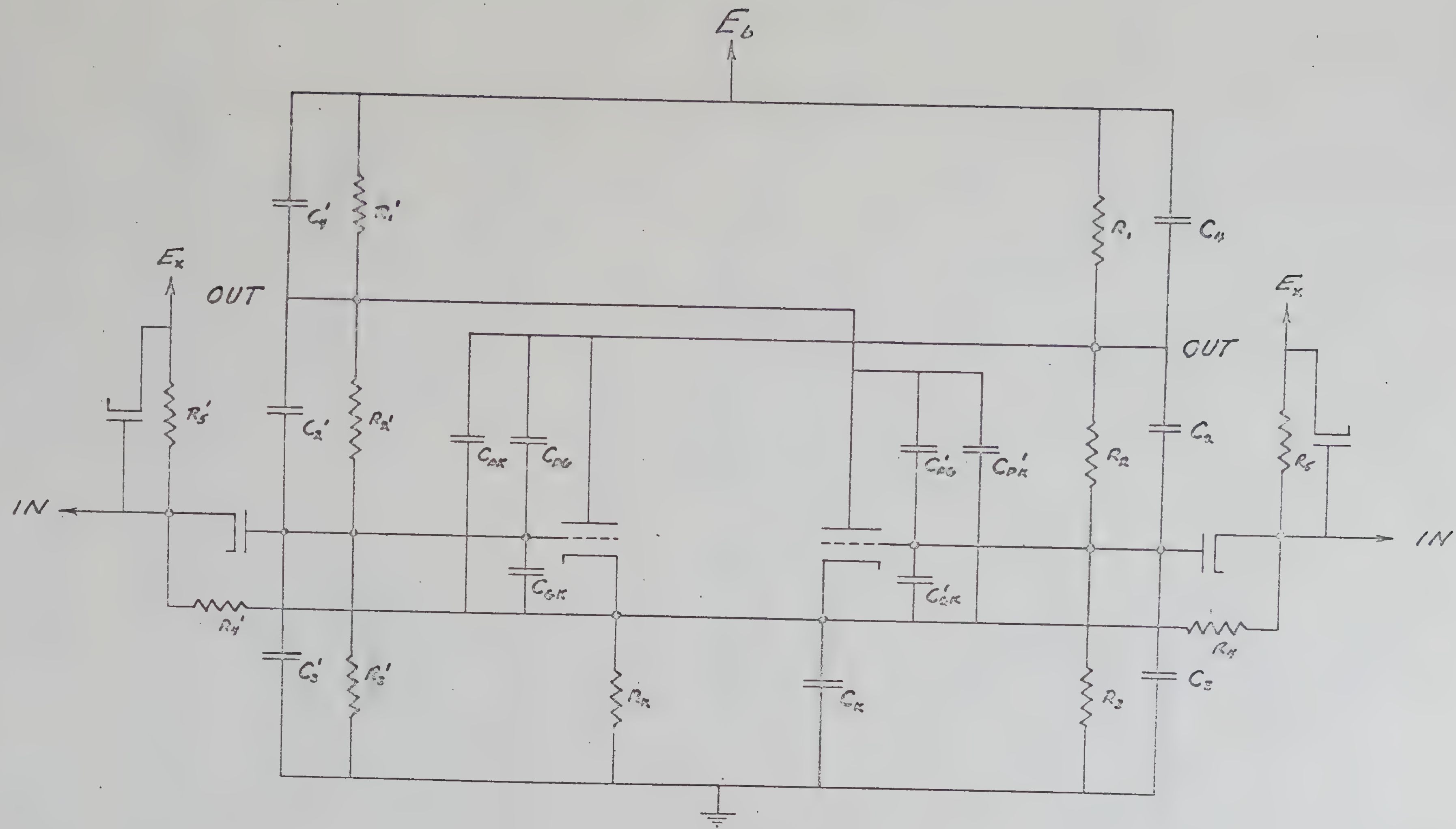
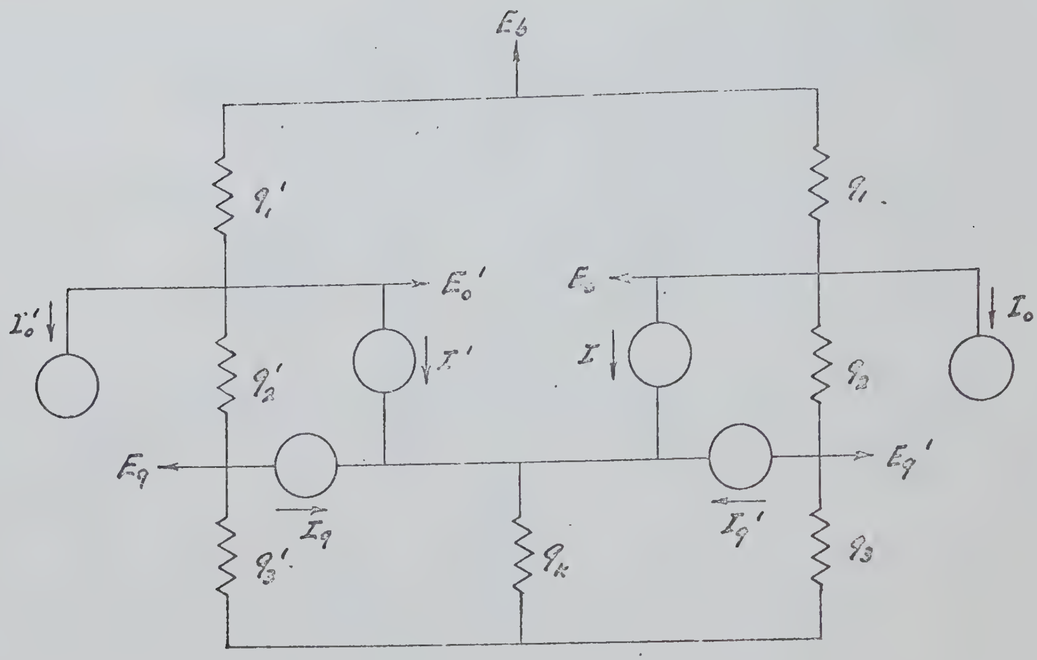


FIGURE 1

BASIC FLIP-FLOP CIRCUIT



I = PLATE CURRENT OF FULLY CONDUCTING TUBE
I'= " " " LESSER " "
I_o= GRID CURRENT OF CATHODE FOLLOWER (LOW SIDE)
I_o'= " " " " " (HIGH SIDE)
I_g= GRID CURRENT OF FULLY CONDUCTING TUBE
I_g'= " " " LESSER " "

STATIC EQUATIONS

$$E_g' = \frac{bg_2 - I_g'a}{ca - g_2^2}$$

$$E_o = \frac{E_g'c + I_g'}{g_2}$$

$$E_g = \frac{b'g_2' - I_ga'}{a'c' - (g_2')^2}$$

$$E_o' = \frac{E_gc' + I_g}{g_2'}$$

$$E_k = \frac{I + I' + I_g + I_g'}{g_k}$$

Where:

$a = g_1 + g_2$

$b = -(I + I_o) + E_bg_1$

$c = g_2 + g_3$

$a' = g_1' + g_2'$

$b' = -(I' + I_o') + E_bg_1'$

$c' = g_2' + g_3'$

FIGURE 2 EQUIVALENT STATIC CIRCUIT

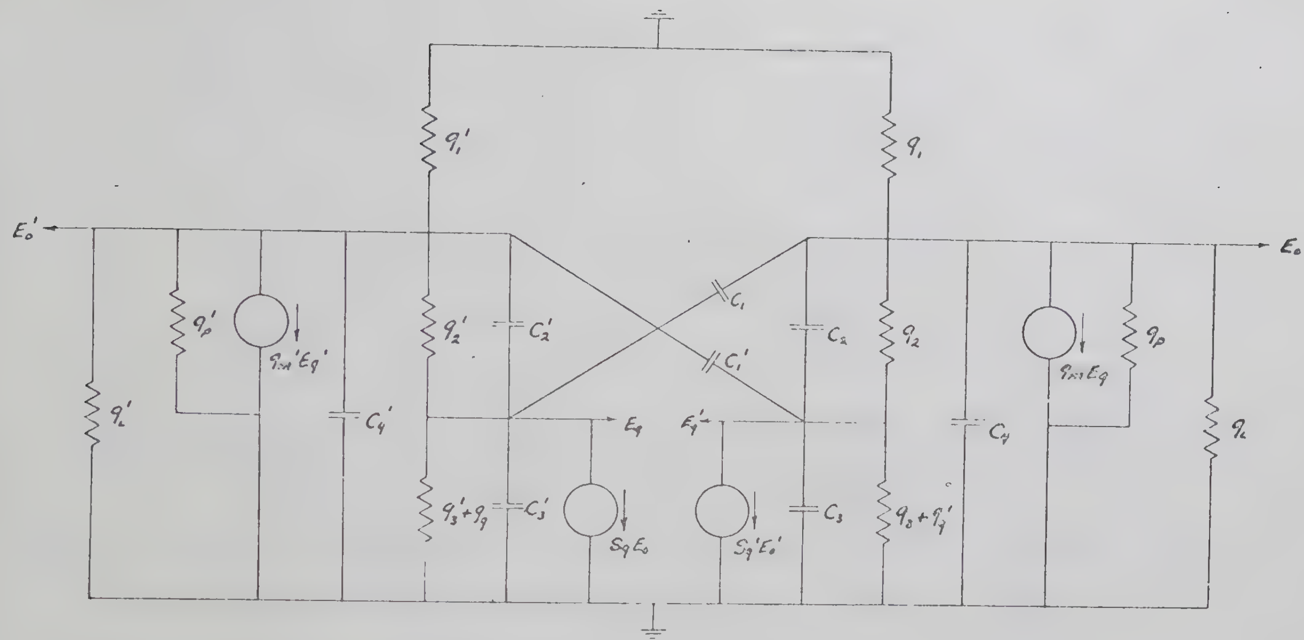


FIGURE 3

EQUIVALENT DYNAMIC CIRCUIT

$a_4 \neq 0$ If $a_4 = 0$ the polynomial is reduced to third order

$$D_1 = \frac{a_3}{a_4} > 0$$

$$D_2 = \frac{a_3 a_2 - a_4 a_1}{(a_4)^2} > 0$$

$$D_3 = \frac{a_3(a_1 a_2 - a_0 a_3) - (a_1)^2 a_4}{(a_4)^3} = \frac{a_1}{a_4} D_2 - \frac{a_0 (a_3)^2}{(a_4)^3} > 0$$

$$D_4 = \frac{a_0 a_3 (a_1 a_2 - a_0 a_3)}{(a_4)^4} - \frac{a_0 a_4 (a_1)^2}{(a_4)^4} = \frac{a_0}{a_4} D_3 > 0$$

FIGURE 4

ROUTH'S CRITERIA FOR HURWITZ POLYNOMIAL

$$\Delta = P^4 a_4 + P^3 a_3 + P^2 a_2 + P a_1 + a_0$$

WHERE:

$$a_0 = a\left[f(g_2')^2 + S_g'gm'f' - ff'b\right] + g_2\left[-g_2(g_2')^2 + g_2bf' + gmgm'g_2'\right] + S_ggmfb$$

$$\begin{aligned} a_1 = {} & a\left[(g_2')^2l + 2g_2'c_2'f - S_g'c_1'f' - c_1'gm'f' + S_g'gm'l' - f'bl - ff'k' - fl'b\right] \\ & + g_2\left[c_2bf' + g_2k'f' + g_2bl' + gmgm'c_2' - (g_2')^2c_2 - 2g_2'c_2'g_2 - c_1gm'g_2'\right. \\ & \left. - gmc_1'g_2'\right] + k\left[f(g_2')^2 + S_g'gm'f' - ff'b\right] + c_2\left[g_2bf' + gmgm'g_2' - (g_2')^2g_2\right] \\ & - c_1gmfb - S_g\left[g_2g_2'c_1' + c_1fb - c_1'gm'gm - lgmb - k'fgm\right] \end{aligned}$$

$$\begin{aligned} a_2 = {} & a\left[2c_2'lg_2' + (c_2')^2f + (c_1')^2f' - S_g'c_1'l' - c_1'gm'l' - fl'k' - lf'k' - ll'b\right] \\ & + g_2\left[c_2k'f' + c_2l'b + g_2k'l' + c_1c_1'g_2' - 2g_2'c_2'c_2 - (c_2')^2g_2 - c_1c_2'gm'\right. \\ & \left. - gmc_1'c_2'\right] + k\left[(g_2')^2l + 2g_2'c_2'f - S_g'c_1'f' - c_1'f'gm' + S_g'gm'l' - f'bl\right. \\ & \left. - ff'k' - fl'b\right] + c_2\left[c_2bf' + g_2k'f' + g_2bl' + gmgm'c_2' - (g_2')^2c_2\right. \\ & \left. - 2g_2'c_2'g_2 - c_1gm'g_2' - gmc_1'g_2'\right] + c_1\left[c_1bf + c_1'g_2g_2' - c_1'gmgm' - lgmb\right. \\ & \left. - k'fgm\right] - S_g\left[c_1'gm'c_1 + (c_1')^2gm + c_2c_1'g_2' + c_2'c_1'g_2 + c_1lb + c_1k'f\right. \\ & \left. - k'lgm\right] \end{aligned}$$

$$\begin{aligned} a_3 = {} & a\left[(c_2')^2l + (c_1')^2l' - ll'k'\right] + g_2\left[c_2k'l' + c_1c_1'c_2' - c_2(c_2')^2\right] + \\ & + k\left[2c_2'lg_2' + (c_2')^2f + (c_1')^2f' - S_g'c_1'l' - c_1'gm'l' - fl'k' - lf'k'\right. \\ & \left. - ll'b\right] + c_2\left[c_2k'f' + c_2l'b + g_2k'l' + c_1c_1'g_2' - 2g_2'c_2'c_2 - (c_2')^2g_2\right. \\ & \left. - c_1c_2'gm' - gmc_1'c_2'\right] + c_1\left[c_1'c_1gm' + (c_1')^2gm + c_1'c_2g_2' + c_1'c_2'g_2\right. \\ & \left. + c_1lb + c_1k'f - k'lgm\right] - S_g\left[c_2c_2'c_1' + c_1lk' - (c_1')^2c_1\right] \end{aligned}$$

$$\begin{aligned} a_4 = {} & k\left[(c_2')^2l + (c_1')^2l' - ll'k'\right] + c_2\left[c_1c_1'c_2' + c_2k'l' - (c_2')^2c_2\right] \\ & + c_1\left[c_1'c_2'c_2 + c_1lk' - c_1(c_1')^2\right] \end{aligned}$$

FIGURE 5

COEFFICIENTS OF 4TH ORDER POLYNOMIAL

$y_{24} = (K)dy_{35}$

$y_{25} = \int (D_o)dy_{67} = D_o gm$

$y_{26} = \int (D_1)dy_{67} = D_1 gm$

$y_{27} = \int (D_2)dy_{67} = D_2 gm$

$y_{30} = \int (D_3)dy_{67} = D_3 gm$

$y_{31} = -\int (y_{35})dy_{25} = -\int gm' \, d(D_o gm)$

$y_{32} = \int (y_{35})dy_{26} = \int gm' \, d(D_1 gm)$

$y_{33} = -\int (y_{35})dy_{27} = -\int gm' \, d(D_2 gm)$

$y_{34} = -\int (y_{35})dy_{30} = -\int gm' \, d(D_3 gm)$

$y_{35} = \int (y_{24} + y_{77})dN = gm'$

$y_{36} = -\int (B_o)dy_{67} = -B_o gm$

$y_{37} = \int (B_1)dy_{67} = B_1 gm$

$y_{40} = -\int (B_2)dy_{67} = -B_2 gm$

$y_{41} = -\int (B_3)dy_{67} = -B_3 gm$

$y_{42} = -\int (C_o + y_{25})dy_{35} = -C_o gm' - \int (D_o gm)dgm'$

$y_{43} = \int (C_1 + y_{26})dy_{35} = C_1 gm' + \int (D_1 gm)dgm'$

$y_{44} = -\int (C_2 + y_{27})dy_{35} = -C_2 gm' - \int (D_2 gm)dgm'$

$y_{45} = -\int (C_3 + y_{30})dy_{35} = -C_3 gm' - \int (D_3 gm)dgm'$

$y_{46} = -S(y_{33} + y_{40} + y_{44} + y_{46})dN = B_2 gm + C_2 gm' + D_2 gmgm' = a_2/a_4 - A_2$

$y_{47} = -S(y_{31} + y_{36} + y_{42} + y_{47})dN = B_o gm + C_o gm' + D_o gmgm' = a_o/a_4 - A_o$

$y_{50} = \int (A_3 + y_{51})dy_{46} = \int (a_3/a_4) \, d(a_2/a_4)$

$y_{51} = -S(y_{34} + y_{41} + y_{45} + y_{51})dN = B_3 gm + C_3 gm' + D_3 gmgm' = a_3/a_4 - A_3$

$y_{52} = -S(y_{32} + y_{37} + y_{43} + y_{52})dN = -(B_1 gm + C_1 gm' + D_1 gmgm') = -(a_1/a_4 - A_1)$

$y_{53} = \int (A_2 + y_{46})dy_{51} = \int (a_2/a_4) \, d(a_3/a_4)$

$y_{54} = \int (y_{55})dy_{52} = \int (-D_2) \, d(-a_1/a_4)$

$y_{55} = -S(-A_1 + y_{50} + y_{52} + y_{53} + y_{55})dN = -\{(a_2/a_4)(a_3/a_4) - (a_1/a_4)\} = -D_2$

$y_{56} = -\int (y_{57})dy_{47} = -\int (a_3/a_4)^2 d(a_o/a_4)$

$y_{57} = \int (2A_3 + y_{51} + y_{74})dy_{51} = \int 2(a_3/a_4) \, d(a_3/a_4) = (a_3/a_4)^2$

$y_{60} = \int (A_1 + y_{52})dy_{55} = \int -(a_1/a_4) \, d(-D_2)$

$y_{61} = -\int (A_o + y_{47}) \, dy_{57} = -\int (a_o/a_4) \, d(a_3/a_4)^2$

$y_{62} = S(A_3 + y_{51})dN$

$y_{63} = S(-A_1 + y_{50} + y_{52} + y_{53})dN$

$y_{64} = S(y_{54} + y_{56} + y_{60} + y_{61})dN$

$y_{65} = S(A_o + y_{47}) \, dN$

$y_{66} = C(y_{35})$

$y_{67} = -\int (-1)dy_{62,63,64,65} = gm$

$y_{74} = -\int (-1)dy_{51} = (a_3/a_4 - A_3)$

$y_{76} = C(y_{67})$

$y_{77} =$ NO CODE — ZERO OUTPUT

WHERE:

$$a_o/a_4 = A_o + B_o gm + C_o gm' + D_o gmgm'$$

$$a_1/a_4 = A_1 + B_1 gm + C_1 gm' + D_1 gmgm'$$

$$a_2/a_4 = A_2 + B_2 gm + C_2 gm' + D_2 gmgm'$$

$$a_3/a_4 = A_3 + B_3 gm + C_3 gm' + D_3 gmgm'$$

FIG. 6 CODING OF DIGITAL DIFFERENTIAL ANALYZER

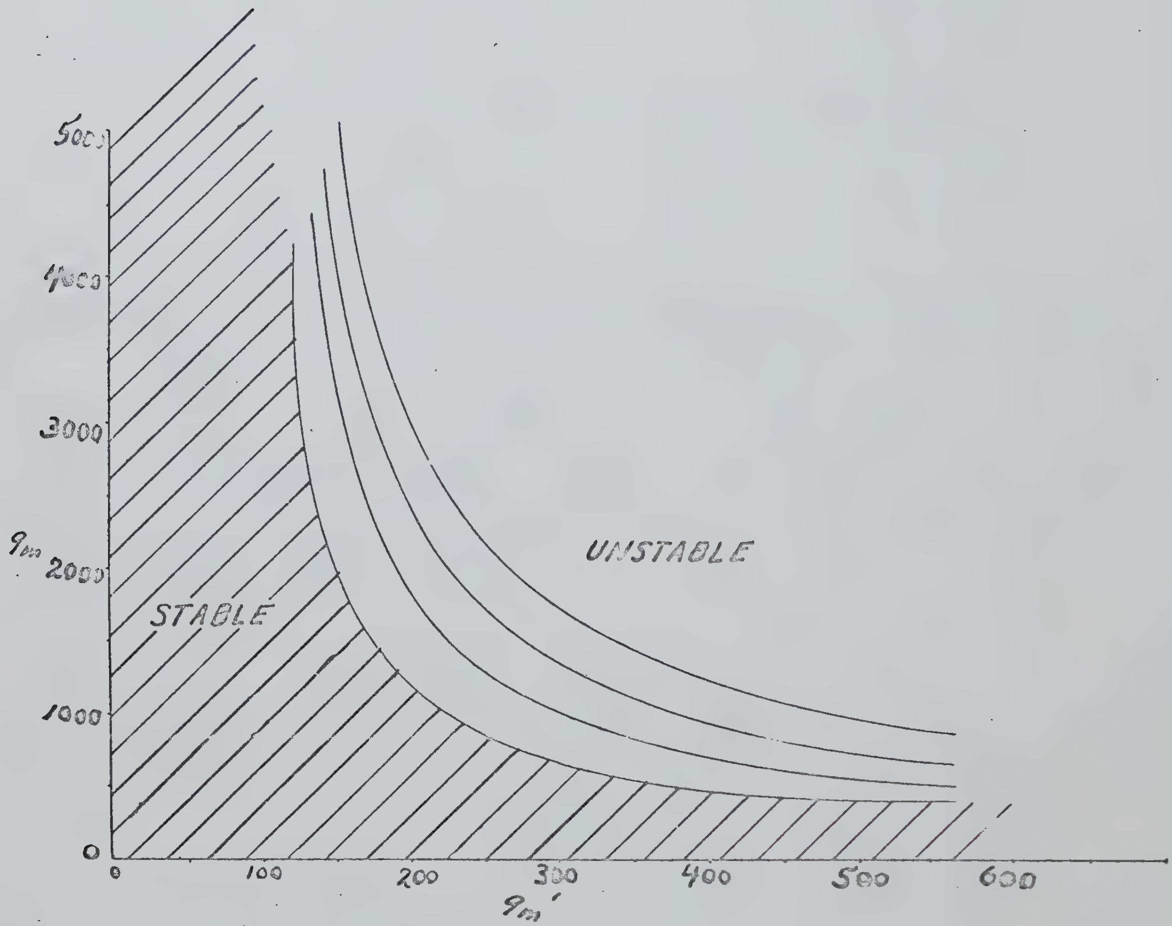


FIGURE 7 DYNAMIC STABILITY PLOT

APPLICATIONS OF CRC-105 DECIMAL DIGITAL DIFFERENTIAL ANALYZER

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Introduction

In the two years since the first digital differential analyzer was put in operation, it has been the complexity of filling and operating such machines, rather than any difficulty in coding them for a problem, that has constituted the main impediment to convenience and efficiency in their use. In filling some hundred-odd binary digits, one at a time, for each integrator information, the possibility of error is great. For instance, let us look at the binary number

.010111101011100001010001111.

The decimal equivalent of binary .010111101011100001010001111 is .370000. Naturally, error is much less likely in filling the 6-digit decimal number than in filling the 27-digit binary number.

Description of CRC-105

Out of these considerations developed the CRC-105 Decimal Digital Differential Analyzer (Figure 1), incorporating a number of features heretofore unknown in digital differential analyzers. The machine is all decimal, has 60 integrators with a maximum accuracy of six digits and sign, and operates at a basic speed of 60 integrations per second for each integrator.

Each of the integrators is provided with a 6-digit constant multiplier varying between +1 and -1, including +1 and -1. This constant multiplier enables the operator to carry through even scales of powers of 10 so that printed values can be scaled by simply placing the decimal point. It also eliminates the heretofore difficult scaling problem. For the convenience of the operator, the machine is so designed that when this constant multiplier is left unfilled, it operates as +1. In this phase of the machine, negative numbers are entered as absolute value and sign, not as complements.

Any one integrator can be coded to act as a limiter, so that a function fed through it will come out within predetermined values--an operation equivalent to limiting the maximum voltage in an analog computer. The output value will stay at the limit until the input value again reaches the limit, and falls within it.

If any integrator should overflow during computation, the machine will automatically stop instantly, unless coded to the contrary, without losing information. Inspection of the indicator lights on the control panel will

reveal which integrator has overflowed. The machine cannot be restarted until the overflow condition has been removed. At the end of this discussion I shall outline several coding tricks which utilize the overflowing of an integrator, in which case such an integrator has to be coded to permit overflow.

The machine has 12 channels for transmitting incremental information while computation is proceeding. Each channel consists of two leads, where a pulse on one lead represents a positive increment, and a pulse on the other lead represents a negative increment; if the function represented by that channel remains constant over any period of time no pulse will be created on either lead.

The machine also has 12 channels for receiving incremental information while computation is proceeding. Each channel consists of two leads, interpreted in the same manner as the outputs described above. Information received through these channels requires no external synchronization, all synchronization being taken care of within the machine. Such information can be coded into any one or several integrators with complete freedom, just as if it were the output of another integrator.

At the main control station there is a built-in Flexowriter electric typewriter (Figure 1) which will type out the contents of the integrand of those integrators which are coded to be typed. This typing is fully automatic, and the machine will stop computation only long enough for the typewriter to type a set of data, regardless of how many integrators form such a set. The point where information should be typed out is computed by the machine itself in any manner desired, which is completely up to the coder. It is possible, for instance, to have data typed out when a certain variable reaches a maximum or minimum, at the final point of computation only, at regular intervals, and so on.

An extra channel is provided in the memory of the machine, to remember the initial conditions of all variables. Very often it is desired to change the initial conditions of some one or two variables, leaving the rest of the problem intact. At the touch of a button, the machine is restored to the original conditions of the problem, and it is only necessary to make the desired changes in filling before running the problem as modified.

Filling and Operating

As was pointed out at the beginning of this article, one of the main features of this machine is the simplicity of filling and operating it. In the upper left-hand corner of the control panel (Figure 2) are two switches which select the integrator to be filled, and a third switch which selects the function of the machine or the channel to be filled. All information pertaining to any integrator (numerical as well as code and hookup information) is filled by means of the standard 10-key decimal keyboard while the selector switches are set to the number of that integrator. Five channels are the maximum to be filled for any one integrator (three coding channels

A_1, A_2, A_3; initial condition, K or Y_1; and constant multiplier, Y_2), each channel containing a maximum of seven decimal digits. Therefore, the operation of filling an integrator requires no more than the typing of five 7-character words on a 10-key keyboard. Consequently, the whole machine, in a problem involving all 60 integrators, can be filled easily in less than 10 minutes, with little likelihood of error. If a record is desired for later checking, initial conditions can then be printed out on the typewriter by throwing the PRINT INITIAL CONDITIONS switch. It has been noted from studying several application problems, that the same initial conditions often appear in two integrators simultaneously. Therefore, a special switch is provided on the control panel which allows the filling of initial conditions of two consecutive integrators at once, still further cutting the filling time.

There are several occasions where obtaining the proper code requires an impossible decimal combination. The required combination is achieved by means of the * (star) key to the left of the decimal keys, which will superimpose a pulse in the 2* position. The machine operates in the 1-2-4-2* number system.

The RESET button brings the machine to the beginning (MSD) of the word of the channel and integrator indicated by the three selector switches. The three lights above the keys indicate which decimal digit of the word is being filled.

On top of the control panel is a visual read-out showing the contents of the channel of the integrator indicated by the selector switches. These lights make it possible to check information while filling or after filling, to take readings between computations, or to check a particular variable at a particular point. The read-out lights are in binary-coded decimal representation and must be interpreted in groups of four.

The key marked C on the right-hand side of the panel will completely clear whichever channel is showing on the selector switch and will clear that channel for all integrators of the machine. This button will also start computation when the selector switch is pointed to COMPUTE, or will transfer the original initial condition from the K channel into the computation channel, Y_1, when the selector switch is pointed to T. It should be pointed out that in case of error or in case some small correction must be made in any channel, filling new information into a given word automatically erases information previously in that position. Consequently, no erasing need be done unless it is desired to clear the whole channel.

This computer can operate with several items of auxiliary equipment. In order to facilitate feeding empirical functions in and out of the machine as computation proceeds, there is provided a graph reader and plotter which has several functions. This equipment is manufactured especially for Computer Research Corporation by the Benson-Lehner Corporation of West Los Angeles. It is capable of reading a graph automatically by means of a line follower and producing a punched paper tape representing the graph for a single-valued

function. It is also capable of plotting a single-valued function from one tape, or a function representing one variable as a function of another from two tapes, where, in turn, each variable is a function of a third. Thus, a multiple-valued function can be plotted from punched paper tapes. The plotter can also plot information directly from the computer without intermediate paper tape, in which case, of course, single- or multiple-valued functions can be plotted, one value against another. The same unit can also feed information directly into the computer at the command of the computer, with the computer controlling the x-axis, and the y-axis variable being fed directly into the computer.

In addition to that equipment, there are tape readers available which feed information into the computer at the command of any variable, as well as tape punches which punch increments of a variable on a paper tape, where each tape axis is a monotonically increasing function of the computer. The only requirement there is that the tape-axis function shall not at any time vary slower than the other variable punched against it.

All these devices feed in and out of the computer through the 12 input and 12 output channels previously mentioned. Figure 3 illustrates the basic hookup of each of these devices. If the problem demands a capacity greater than 60 integrators, several machines can be interconnected through these channels, with no intermediate equipment.

The 12 input and 12 output channels can also be connected to digital instruments and actuators. The computer can thus be used as a simulating device.

Coding

Now let us look for a moment at the coding of a machine of this sort. The coding is essentially the same as for a Bush-type differential analyzer, with each integrator capable of accepting the sum of as many as seven variables as components for the integrand. Consequently, a summing device is not usually necessary. However, if the sum of several variables is to be fed into an integrator as the independent variable for that integrator, it can be introduced by means of a trick hookup (Figure 4*) provided that the sum in question does not exceed the machine rate over a given period of time. The reason for this hookup is that an overflow from +0.999999 spills into -1.000000, and an overflow from -1.000000 spills into +0.999999. Consequently, any integrator in which such overflow is desired must be coded to permit overflow without stopping the machine.

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*In these sketches, it should be understood, the integrand feeds into the lower part of each hookup, the independent variable for the particular integrator feeds into the top, and the output of the integrator appears in the center. In the lower part of the integrator box appears the content or value of the integrand, or, in an operational integrator, whatever takes the place of the integrand. Where the integrator box comes to a point, at the right, appears the constant multiplier, if any.

Using the same operational feature, an integrator can be hooked up to act as a servo (Figure 4). In this case a variable (u) is given, to represent a function of another variable (v). The negative value of (u) is then generated as a function of an assumed variable (v), a comparison is made against the given function, and the independent variable (v) is corrected so that the generated function matches the given function. The comparison is made in an operational integrator which makes use of the fact that +0.999999 overflows into -1.000000 and vice versa.

A third application of this feature is the use of an integrator to achieve multiplication of a variable rate by a constant greater than unity (Figure 4).

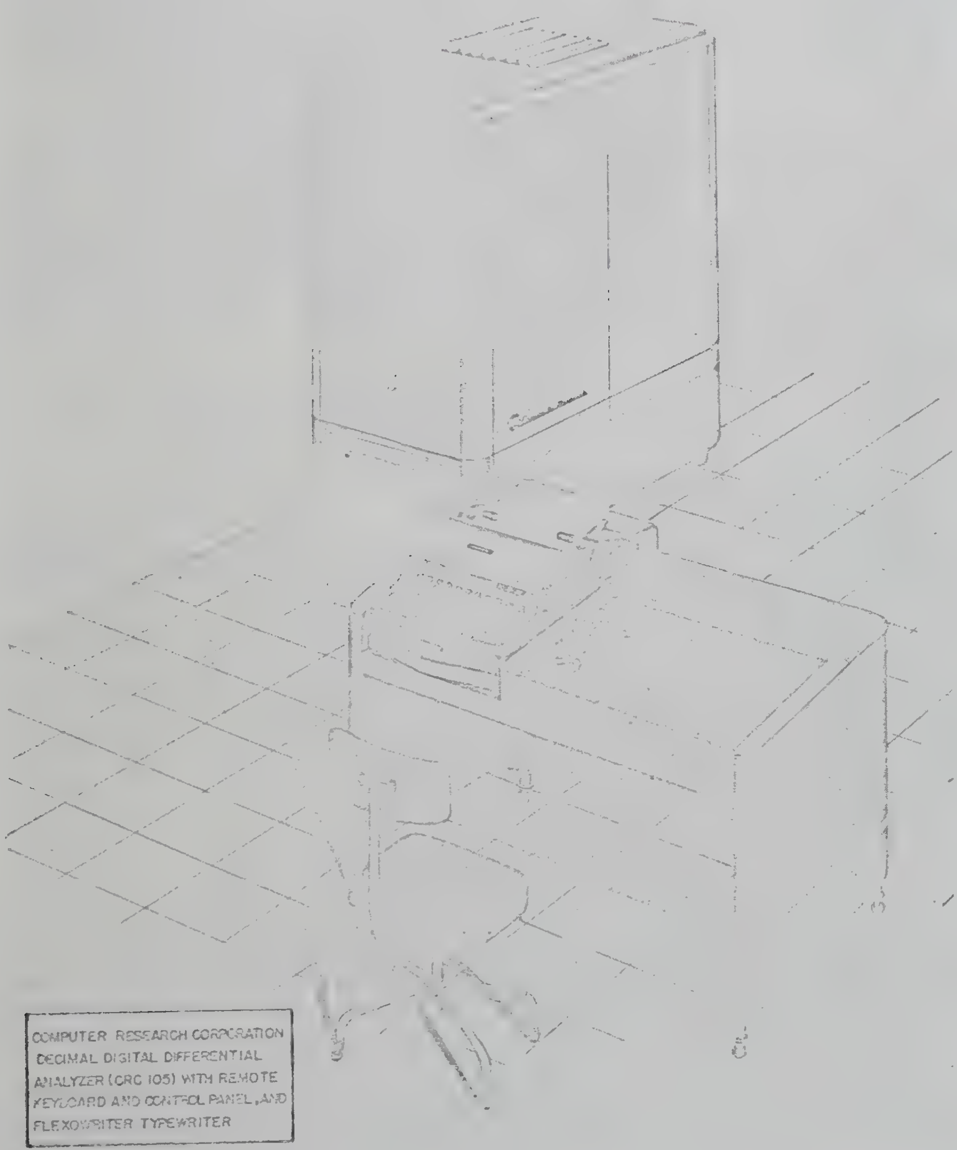


Fig. 1

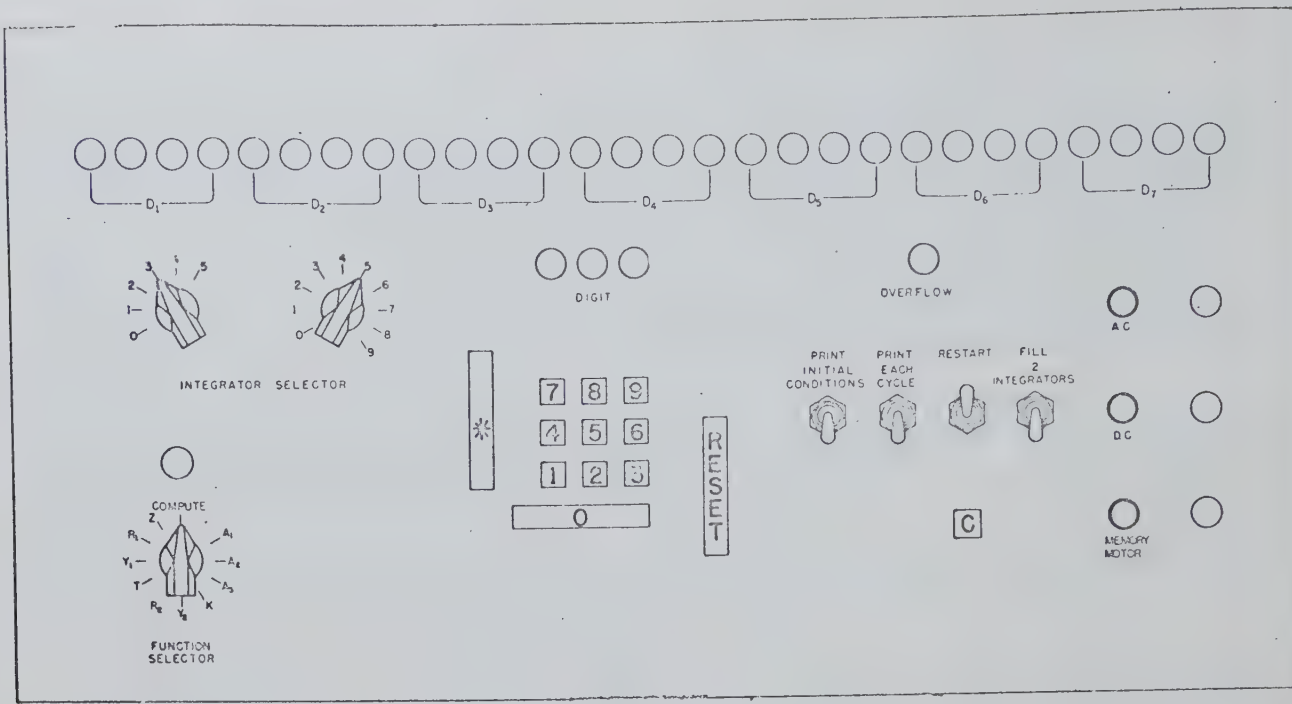
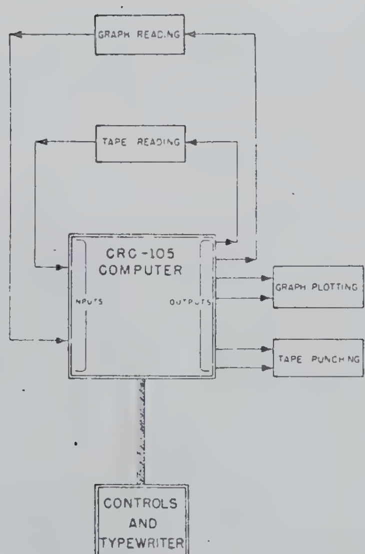


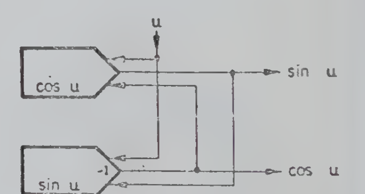
Fig. 2

CRC-105 REMOTE KEYBOARD AND CONTROL PANEL

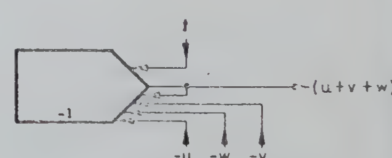


CRC-105 AUXILIARY EQUIPMENT OPERATIONAL SCHEMATIC

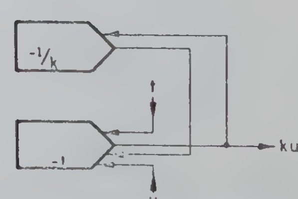
Fig. 3



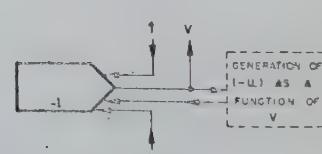
GENERATION OF SINE AND COSINE OF A VARIABLE u



SUMMING OF SEVERAL VARIABLES



MULTIPLICATION BY A CONSTANT, k, WHERE k > +1 OR k <



~~SERVO GENERATION~~ OF V FROM u, WHERE u IS GIVEN AS A FUNCTION OF V

Fig. 4

CRC-105 Integrator Hookups

MULTIDIMENSIONAL MAGNETIC MEMORY SELECTION SYSTEMS

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I. Introduction

Many investigators have for several years been studying the use of rectangular loop magnetic cores as memory elements. It seems profitable at this time to examine, from a dimensional point of view, the various selection systems which have been developed, and to find the relations between their operating principles.

The selection systems to be discussed operate on information in parallel fashion. Systems using time as one of the storage co-ordinates, such as delay lines, will not be included in this examination.

The selection problem is that of either reading the information stored in a particular group of elements, or storing information in a group of elements. During storing it must be possible to write one's or zero's arbitrarily in the various elements of a group, or word. The chosen means of performing this write switching must in a parallel system be independent of the means of word selection.

Let us now define the number of dimensions of a storage and selection array. We shall count one dimension for every set of driving lines (or vacuum tubes, saturable cores, etc.) such that there is one and only one line of each set which must be activated (or conversely, not activated) for any group of storage elements which may be selected. We shall count one extra dimension also for write switching. The number of dimensions then conveys the degree or number of coincidences which must be sensed by the magnetic elements and by the mode of their internal connections in the array during the write operation. It does not include, of course, the selection operations which may be performed external to the array proper by use of diode switches, magnetic devices, or other means of performing logical operations.

II. One Dimensional Selection Systems

As an example of a one dimensional selection system we may examine the magnetic storage of the JAINCOMP-B computer,[1,2] made by the Jacobs Instrument Company. This method of storage selection uses equipment which directly selects the desired elements uniquely, and performs the desired operation on them. It is an extremely simple method, it renders a high speed system possible using inherently low speed magnetic materials, and it places a minimum of quality control restrictions on the magnetic elements.

III. Two Dimensional Selection Systems

An example of a two dimensional selection system is found in the magnetic storage for the ENIAC[3] being made by the Burroughs Adding Machine Company. This system utilizes both ends of the core windings in performing write switching. Biased diodes are used to prevent multiple paths through the array. This method also allows very rapid operation to be achieved even with very low speed magnetic materials, and does not require the cores to have stable minor loops at the remanence points.

Another two dimensional system may be generated by the use of coincident currents, first suggested by Forrester,[4] as a means of write switching. A 2:1 ratio of MMF's is used in writing, and the ratio attainable in reading is essentially infinite. The writing ratio may be increased to 3:1 by use of currents to prevent writing as well as to cause writing.

IV. Three Dimensional Selection Systems

An example of a three dimensional selection system is the memory being studied at MIT for application to the Whirlwind Computers.[5] This system involves the coincidence of two currents for selection, and anti-coincidence with digit currents for write switching. A 2:1 ratio of MMF's is obtained both in reading and writing.

The coincident current technique can be directly extended to systems of more than three dimensions.[6] This involves the coincidence of more than two currents, and consequently lowered MMF ratios. The maximum obtainable ratios are shown in Figure 1. When n currents are used for selection (not including the digit writing currents), the ratio is $n/n-1$. When four or more currents are used in selection, an improvement may be had by application of a biasing MMF to the entire array. When full bias is used, the ratio is $n + 2 + \alpha/n + \alpha$; where α is zero, for n even, and α is one, for n odd. The worth of bias is limited by the difficulties of supplying it in such fashion that the desired MMF ratios are preserved throughout the transient states.

Another three dimensional selection system may be generated by use of a matrix principle for selection.[7] This is shown in Figure 2. It utilizes the fact that any winding, or series chain of windings, has but two terminals; and that current flowing through must enter at one terminal, leaving at the other. The matrix lines may be driven in such fashion that current enters on one of the x lines, flows through the selected group of elements, and leaves the array on one of the y lines. The other lines may be constrained to have zero current, or to be open circuits.

A serious defect of matrix selection on this principle is the existence of multiple paths through the array. If no corrective measures are applied, the magnitude of the largest multiple path current will be of the order of one-

half that of the selected group current. However, the insertion of non-linear elements in series with each storage group reduces these multiple path currents to a reasonable value.

If write switching is done by current coincidence, and selection by the matrix method, the MMF ratios are 2:1 for writing and essentially infinite for reading. The writing ratio may be increased to 3:1 by use of additional currents to inhibit writing.

Figure 3 shows these two methods combined in an array. The chosen co-ordinates, x_s and y_s, determine the selected word. Coincidences with the various z plane currents determine the one's or zero's being stored. Figure 4 shows one mode of physical realization of such a system. It employs vacuum tubes as the driving elements, and diodes as the non-linear elements for multiple path current reduction. Only a four word capacity is shown, and both output and digit input windings have been omitted from the drawing. Figure 5 is a block diagram for a capacity of 4096 words, showing diode read-write gates, and diode matrices for address decoding.

A grave difficulty is the large number of diodes required for multiple path current reduction. Furthermore, the front-to-back resistance ratio required of them is quite severe. An array of n^2 words requires $2(n^2)$ diodes, since a diode is unidirectional as well as non-linear. If we assume as a reasonable criterion that the maximum allowable total current for all multiple paths should be less than or equal to the current in the selected path, then the diodes must meet the requirement that $R_f/R_b \leq 1/(n-1)^2$. The severity of this requirement may render a large scale system of this type impractical. The number of driving tubes is $3n + 2d$, for d bits per word.

The three dimensional matrix system can be realized in a more practical fashion, though applicable only to a very low speed range, by the use of relay points to perform not only selection of the matrix line, but also to completely eliminate multiple paths. Since relay points are bidirectional, n^2 points will suffice for multiple paths and for one dimension of matrix selection. They are arranged in n groups, each group having n points which operate together. n single point relays will suffice for the second dimension of matrix selection, $(d + 1)$ points will control bit inputs and perform read-write gating. This is a total of $n^2 + n + d + 1$ relay points.

V. Five Dimensional Selection Systems

A five dimensional selection system can be generated by further combination of the coincident current and matrix systems. The matrix principle is applied to select currents through the array which in turn coincide to select the desired word. The operation principle is partly shown in Figure 6: as in the MIT three dimensional system; the chosen elements lie on the intersection of two planes, the $x_s y_s$ plane and the $x_s' y_s'$ plane, and in one or more z planes.

The difference lies in that the $x_s y_s$ plane, for example, is not chosen directly, but by the independent choices of the x_s and y_s co-ordinates in a matrix system. Thus four co-ordinates must be chosen, one in each dimension, to select the word whose address may be given as $x_s y_s x_s' y_s'$. As before, anti-coincident z plane currents must be supplied for write switching. MMF ratios of 2:1 are obtained during both the read and write operations.

The five dimensional combination system may be physically realized by use of vacuum tubes as the driving elements, and diodes as the non-linear elements for multiple path current reduction. Figure 7 is a block diagram of such a system for a capacity of 4096 words. The saving in numbers of diodes and driving tubes, and in the reduced complexity of the address decoding matrices, will be apparent. An array of n^2 words has two matrix systems, each of $\sqrt{n} \times \sqrt{n}$ size and each containing 2n diodes. The diode requirement, based on the same criterion as before, is that $R_f/R_b \leq 1/(\sqrt{n}-1)^2$, which is realizable even for fairly large arrays. The number of driving tubes is $6\sqrt{n} + d$, for d bits per word.

Relay points may be used as a slower speed means of physical realization. The manner of connections is analogous to the three dimensional case, but the total number of relay points required is reduced to $2n + 2\sqrt{n} + d + 1$ for five dimensions.

VI. Higher Multidimensional Selection Systems

Selection systems of more than five dimensions may become possible if and when magnetic cores can be made with sufficient uniformity and minor loop stability to be useable with MMF ratios of less than 2:1. If a 3:2 ratio is possible, then three coincident currents may be used to select a word. Applying the matrix technique to three currents generates a seven dimensional system. By use of a biasing MMF of a value equal to that of one of the coincident currents, the same 3:2 MMF ratio may be obtained while increasing the number of coincident selection currents to four. Application of the matrix technique to these four currents generates a nine dimensional system.

Figure 8 compares the salient features of several selection systems, of various dimensions, for a parallel storage of n^2 words of d bits each. The numerical values are for the particular case of n^2 equal to 4096 and d equal to 40. The nine dimensional case has not been evaluated since the eighth root of 4096 is not an integral power of two.

VII. Conclusions

The use of matrix selection of coincident currents appears to be a promising method of improving the selection efficiency of large scale magnetic memory systems. Although the five dimensional system has been experimentally proven to be basically operable, a large amount of development re-

mains to be done to find the optimum method of applying combinational selection methods of this type.

VIII. Acknowledgment

The many contributions to the multidimensional concept made by Mr. R. G. Counihan and Mr. G. E. Whitney, of the IBM Poughkeepsie Laboratories, are very gratefully acknowledged.

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n	R_O	B	R_B
2	2:1	0	2:1
3	3:2	0	3:2
4	4:3	1	3:2
5	5:4	1	4:3
6	6:5	2	4:3
7	7:6	2	5:4
8	8:7	3	5:4

$R_O = \frac{n}{n-1}$ = RATIO OBTAINABLE WITHOUT BIAS MMF

$R_B = \frac{n-B}{n-1-B} = \frac{n+2+\alpha}{n+\alpha}$ = RATIO OBTAINABLE WITH USE OF MAXIMUM BIAS MMF

$B = \frac{n-\alpha-2}{2}$ = RATIO OF MAXIMUM BIAS MMF TO ONE UNIT SELECTION MMF

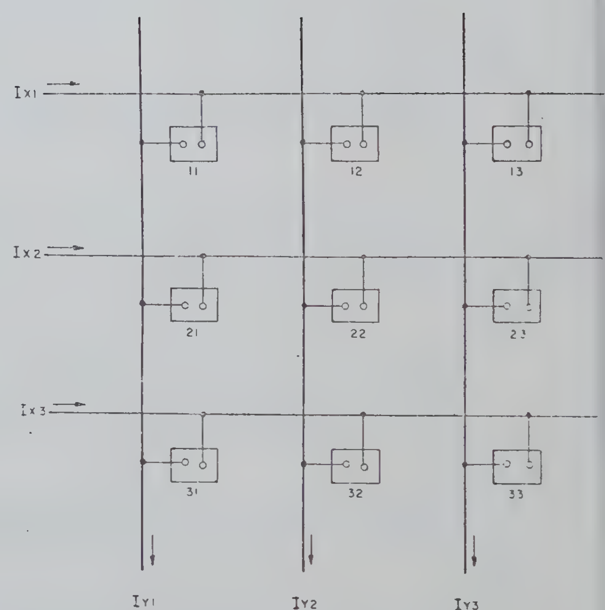
n = NO. OF SELECTION MMF'S

$\alpha = 0$, n EVEN

$\alpha = 1$, n ODD

COINCIDENT CURRENT SELECTION RATIOS

FIG. 1



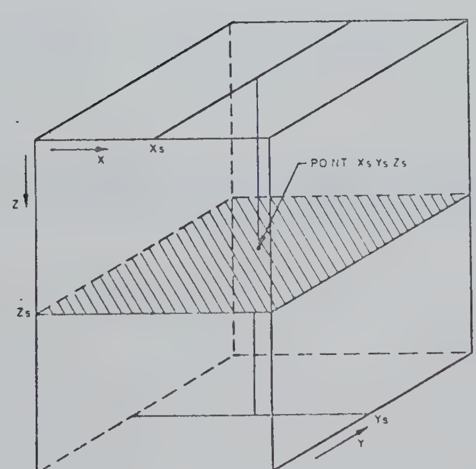
TO SELECT GROUP pq:

LET $I_{xp} = I_0$, $I_{yq} = I_0$,

AND $I_{xn} = I_{ym} = 0$ FOR $n \neq p$, $m \neq q$.

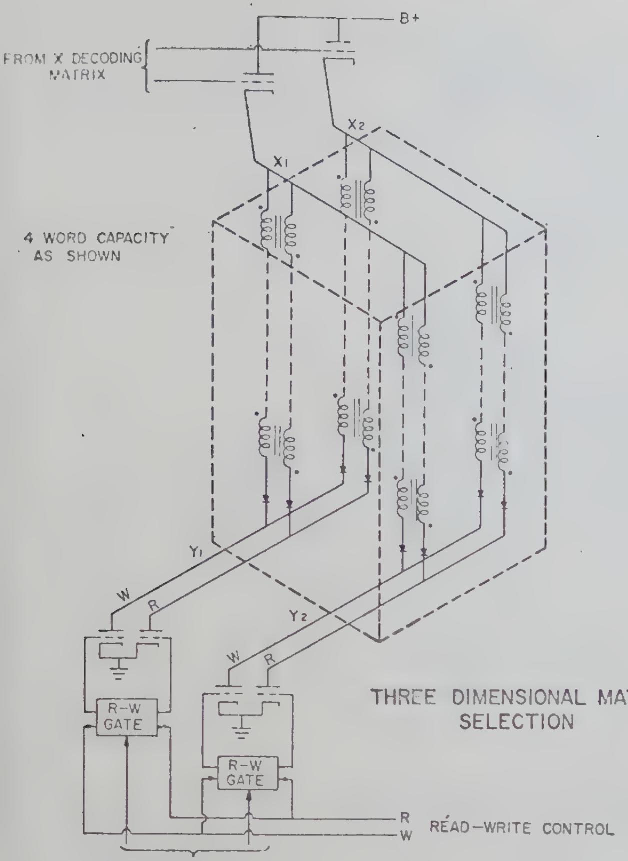
MATRIX SELECTION PRINCIPLE

FIG. 2



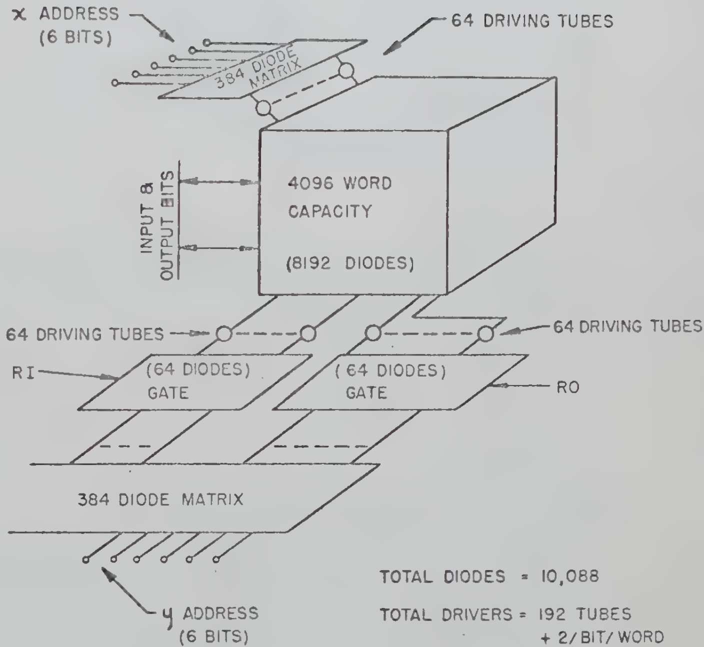
3 DIMENSIONAL MATRIX SELECTION

FIG. 3



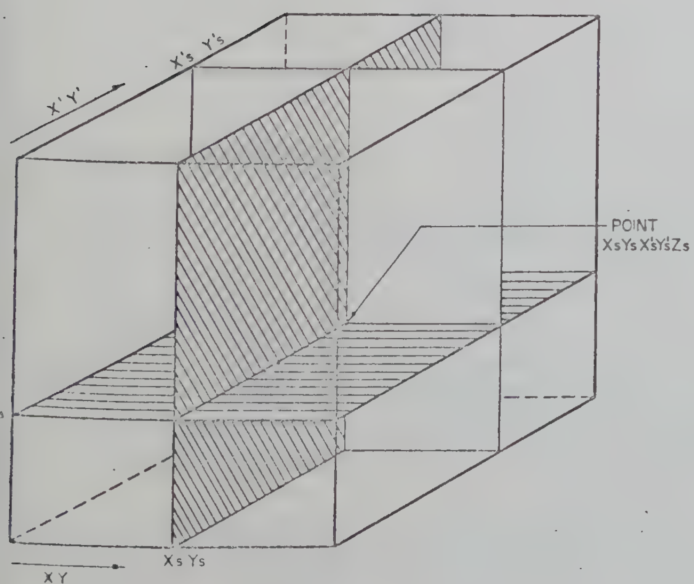
THREE DIMENSIONAL MATRIX SELECTION

FIG. 4



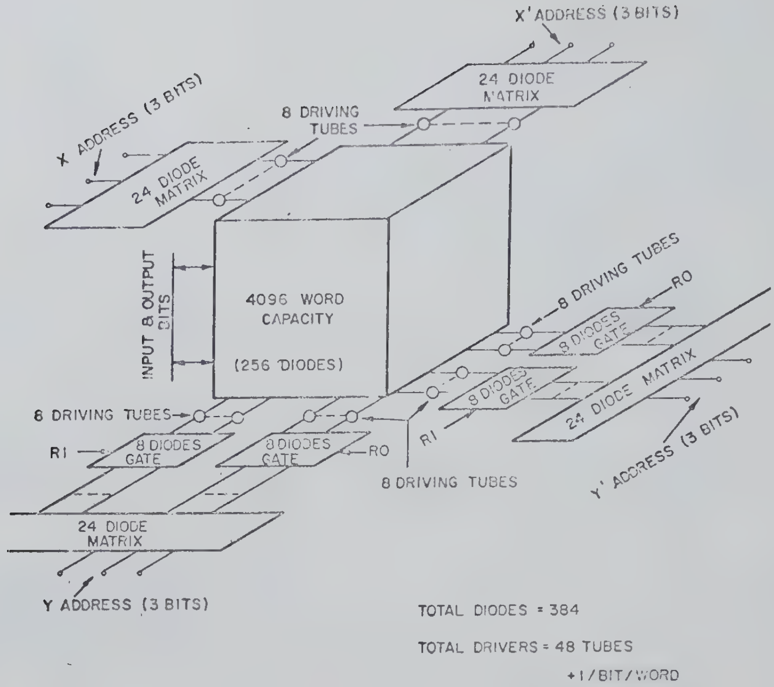
4096 ADDRESS 3 DIMENSIONAL MATRIX SELECTION SYSTEM

FIG. 5



FIVE DIMENSIONAL MATRIX SELECTION

FIG. 6



4096 ADDRESS FIVE DIMENSIONAL MATRIX SELECTION SYSTEM

FIG. 7

n^2 WORDS d BITS/WORD	3 — DIMENS. COINCIDENT CURRENT	3 — DIMENS. MATRIX	5 — DIMENS. MATRIX COINCIDENT CURRENT	7 — DIMENS. MATRIX COINCIDENT CURRENT	9 — DIMENS MATRIX COINCIDENT CURRENT
MMF RATIO: READING	2:1	∞	2:1	3:2	3:2
MMF RATIO: WRITING	2:1	3:1	2:1	3.2	3.2
NO. OF DRIVING ELEMENTS	$4n + d$ 296	$3n + 2d$ 272	$6n^{\frac{1}{2}} + d$ 88	$9n^{\frac{1}{3}} + d$ 76	$12n^{\frac{1}{4}} + d$ ——
NO. OF DIODES FOR MULTIPLE PATHS	0 0	$2n^2$ 8192	$4n$ 256	$6n^{\frac{2}{3}}$ 96	$8n^{\frac{1}{2}}$ ——
NO. OF DIODES FOR RECTANGULAR DECODING MATRICES	$2n \log_2 n$ 768	$2n \log_2 n$ 768	$2n^{\frac{1}{2}} \log_2 n$ 96	$2n^{\frac{1}{3}} \log_2 n$ 48	$2n^{\frac{1}{4}} \log_2 n$ ——
BIAS MMF	0	0	0	0	1 UNIT
NO. OF RELAY POINTS (NOT INCLUDING DECODING)	$2n+d+1$ 169	$n^2+n+d+1$ 4201	$2(n+n^{\frac{1}{2}})+d+1$ 185	$3(n^{\frac{2}{3}}+n^{\frac{1}{3}})+d+1$ 101	$4(n^{\frac{1}{2}}+n^{\frac{1}{4}})+d+1$ ——
NO. OF RELAY POINTS FOR DECODING TREES	$4(n-1)$ 252	$4(n-1)$ 252	$8(n^{\frac{1}{2}}-1)$ 56	$12(n^{\frac{1}{3}}-1)$ 36	$16(n^{\frac{1}{4}}-1)$ ——

COMPARISON OF SELECTION SYSTEMS

FIG. 8

EVALUATED NUMERICALLY FOR $n^2 = 4096$, $d = 40$

OPERATING EXPERIENCE WITH UNIVAC SYSTEMS

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Introduction

In December 1951, at the joint AIEE/IRE Computer Conference held in Philadelphia, several papers were given which discussed the performance of a single UNIVAC SYSTEM* during its first eight months of operation. Although only eight months have passed since that performance summary was given, a much greater effective length of time has passed because three more UNIVAC SYSTEMS have been put into operation since then, and their records together with those of the first system constitute many more months of operation. This paper, therefore, forms an extension of the earlier paper in which we have the good fortune of being able to confirm a number of the predictions and estimates mentioned in the earlier work.

Although many of you may already be quite familiar with the operating features of the UNIVAC SYSTEM, it is undoubtedly worthwhile to review them briefly as a preliminary to the evaluation of the performance of the several completed systems which we have constructed.

The Physical Organization

The physical organization of the UNIVAC SYSTEM centers upon one large cabinet which houses the central computing circuits. This cabinet is shown in figure 1. Extending in a line from one corner of the Central Computer toward the right of the figure are the UNISERVOs* which are the high-speed magnetic tape input-output devices. The Central Computer is directly connected to all of the UNISERVOs and it is possible to associate as many as ten UNISERVOs with one Central Computer. If the problems to be solved do not demand this many devices no alterations are necessary in order to control fewer than the maximum number.

To the left of figure 1 is shown a small part of the Supervisory Control desk. A full view of the control panel is shown in figure 2. The Supervisory Control Panel provides the operator with all the essential control keys necessary for him to assert complete control over the internal operations of the Computer and the UNISERVOs, or to free the Computer of operator control and allow it to perform the programmed operations automatically. In addition, the Supervisory Control Panel provides at all times a complete picture of operating conditions. The numerous error circuits terminate with indicator lights on the panel for observing the correct functioning of the arithmetic operations. These error circuits, as well as the fusing and voltage monitoring indicators, provide simplified location of circuit faults which may occur.

Associated with the control panel is an input keyboard by means of which limited amounts of input data can be inserted, or, more particularly, the operator or maintenance man may alter small amounts of data in the memory during

*Registered Trade Mark

program de-bugging or maintenance procedures. Beside the Supervisory Control desk is a Printer Dolly carrying a typewriter for printing out small amounts of data. The typewriter forms a logical counterpart to the input keyboard.

The remaining sections of the UNIVAC SYSTEM consist of units which are completely separate from the Central Computer. In figure 3 is shown the UNITYPER* which is the keyboard to magnetic tape device. The UNITYPER is useful wherever input data originates in any written or typed form. In figure 4 is shown the Card-to-Tape device which serves the same basic purpose as the UNITYPER except that it operates from data already in existence on punched cards. In figure 5 is shown the UNIPRINTER*, the principle output device. Tapes recorded by the UNISERVO can be mounted on the UNIPRINTER in order to obtain typewritten copy of the data on the tape.

At the present time a high-speed printer is being developed which will be available in 1953. An entirely new Card-to-Tape Converter based on experience with our present Converter also will be available in 1953. This new Converter will be a self-checking device which will handle mark sensed cards as well as punched cards. Odd length stub cards will also be handled.

Operational Specifications

The UNIVAC Central Computer responds to 43 different commands. Among these commands or instructions the usual arithmetic and logical operations are present as well as a variety of input-output instructions. In figure 6 is shown a simplified block diagram of the entire Central Computer. To the right are shown the I and O registers. It is possible to read a block of 60 words of information from a tape into the I tank or register and simultaneously read from the O tank to another tape while internal operations are occurring within the arithmetic section. Since the time required for transfer between a tape and the I or O register is great compared with the time for arithmetic operations, this arrangement economizes on time for any problems requiring large amounts of input and output transfers. Once the data is in the I register a relatively short time is required to transfer from I to the memory. The reverse operation, from the memory to the O tank, takes an equally short time. In the upper left section of the figure are shown the control circuits which govern the internal operations in accordance with the program provided. In the lower section of the figure is shown the arithmetic section of the Computer. The UNIVAC is a serial type Computer having a single transfer bus which has communication with all the registers and the main memory. The memory is a mercury type acoustic delay line system capable of storing 1000 12 character words in addition to the 120 words of input-output storage.

The operational description of the UNIVAC is not complete until mention is made of the ability of the UNIVAC to handle coded representations of alphabetic characters. Each character (numeric or alphabetic) utilizes seven binary impulses. The UNIVAC can be assigned such tasks as alphabetizing and arranging of mixed numerical and alphabetical material.

In order to provide the highest reliability of operation, numerous checking circuits are included throughout the Central Computer, UNISERVOs and the

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auxiliary components. The checking circuits operate on two basic principles. The one principle depends on the coded representations of the various characters constructed on an odd-even relationship by which the number of binary ones appearing in any code is always odd. The other checking principle is based upon duplication of units and comparison, the duplicate units operating simultaneously on the same data. The latter type of checking circuit appears only in the Central Computer, but has been carried as far as was thought feasible to assure correct operation and make trouble location as fast as possible.

Problems Which Have Been Solved By UNIVAC

During the past eight months ample opportunity to test the UNIVAC SYSTEM on all types of problems has been available. The wide scope of problems which can be solved by the UNIVAC SYSTEM is due not only to its alphabetic and numerical features, but also to its high-speed input-output system. The availability of ten high-speed tape devices at any one time has permitted the solution of many problems dealing with very large masses of data. During the solution of these problems the magnetic tapes were used as large storage devices which augmented the high-speed mercury delay line memory. Although the access time for tape recorded data is many times longer than that of the mercury memory, the design of the UNIVAC includes a certain amount of parallel operation which reduces this access time. It is possible to read data from one tape, record data on another tape while simultaneously carrying on internal computations. Fullest advantage of this operation is realized by proper programming.

Matrix Algebra Problem - One of the problems which best illustrates these features is the Matrix Algebra Problems. A report on this computation was delivered at the ACM meeting in Pittsburgh on May3, 1952 by H. Rubinstein and J. Rutledge. Briefly, the Matrix Algebra programs were prepared to multiply and invert matrices up to the order 300 X 300, and to edit the resulting output. The matrices are partitioned into sub-matrices of order 10 X 10 or smaller. One set of programs, referred to as "low-level", performs the multiplication and inversion of the sub-matrices; another set of programs, referred to as "high-level", treats the sub-matrices as elements of a larger matrix in directing the operation of the low-level routines.

The elements are carried in a floating decimal form, with ten significant digits and a sign. The elimination method is used to obtain an inversion, with successive iterations for the improvement of the error sub-matrix. The times for inverting a matrix are:

Order 50 X 50.......1 hour
Order 100 X 100.....8 hours
Order 200 X 200....57 hours
Order 300 X 300...200 hours

The times for multiplying two matrices are roughly the same. During the past eight months the following matrices have been calculated: (40 X 30), (30 X 30), (30 X 10), (10 X 10) with check multiplication; and inversion of

(45 X 45), (40 X 40), (50 X 50), and (200 X 200) matrices all with check.

Trajectory Computation - Another problem of a purely mathematical nature required the plotting of sixty trajectories. The effects of the aerodynamic properties of the projectile were included in the basic trajectory equation. A simple point-by-point integration scheme based on Taylor's series was used. The initial interval was 0.01 seconds which was later changed to 0.10 second after the transients died out. The scheme permitted a 60 second trajectory to be computed in three minutes. Ten significant results (height, distance, velocity, etc.) were printed for each point. Since these results were stored on magnetic tape during the calculation, the computation time was not increased by the printing. A second phase of the problem correlated the range with the initial conditions. A fifth degree polynomial in three variables was chosen to represent the range. The 56 coefficients of the polynomial were evaluated by inverting a 56 X 56 matrix representing the initial conditions and then multiplying by the range vector.

Atomic Energy Problem - Since the spring of 1952 the Atomic Energy Commission has submitted for solution nine different large-scale problems involving the numerical solution of sets of partial differential equations. More than 5000 personnel hours have been devoted to this work, and the UNIVACs themselves have been working for a total of 1700 hours toward their solutions.

Over the entire range of time, 1500 hours of the total computer time have been divided equally between UNIVAC No. 1 (Census Bureau) and UNIVAC No. 3 (Army Map Service). UNIVAC No. 4 contributed an additional 150 hours prior to its acceptance test, and 50 hours since the acceptance test. Relatively little difference in the performances of the three machines has been noted.

During the 1700 UNIVAC hours, the Computers were operative 84.5 % of the time. The remaining 15.5 % of the time was devoted to unscheduled maintenance on the part of the engineers and operators. An additional 3.7 % of the time was spent recomputing lost values because of Computer troubles.

Primarily because it was decided to use a fixed decimal point and to scale all numbers accordingly, a larger amount of time has been spent in "bugshooting" than might normally be expected. This has been responsible for 28.2 % of the 1700 hours.

The nine problems solved on the UNIVAC will be designated A,B,C,D,E,F,G, H, and I for convenience. Some are completed; others are still producing; still others are just emerging into the first stages of Computer-checking.

Problem A has three distinct variations, two of which have been completed. Over 700 computer hours have been spent on the three variations of this problem.

Problem B has been finished, and used 130 hours of productive time. In

addition to this time, however, more than 200 additional hours were spent, largely in the preparation of subsidiary routines of applicability to the AEC projects, and of equal interest to the computer field in general. The first of these is of the nature of a codecheck, wherein a master routine follows the stepwise progress of each instruction in a coded program. Whenever a calculation of significance has been performed, this "Automonitor" routine causes that result to be printed out on the Supervisory Control printer. Whenever a decision is made by the computer, appropriate information concerning the selection made is written out on the Supervisory Control printer. This Automonitor Routine will prove invaluable in the bug-shooting phases of later problems.

A second routine of general interest was the preparation of a graph edit. In problems involving partial differential equations, a great amount of numerical results is to be expected. This information will invariably convey a more ready assessment of results if it is graphed. The graph edit is designed to do just this -- the values of a function versus selected values of the independent variable are computed. Using a sheet of paper allowing 100 spaces across the page, the various values of the function at each value of the independent variable can be charted automatically. The results of this first graph edit proved so valuable that a second graph edit was prepared. In this case, six functions instead of one are simultaneously graphed. This routine has only recently been put into production, and has been applied to the output of one of the completed problems.

A third subsidiary routine of general interest is one which evaluates the relative accuracies of various numerical integration formulas for specific ranges, for specific intervals, and for various types of functions.

Problem C has had thirteen variations to date, of which ten are completed. The time consumed in solving each of the variations ranged from 2 1/2 hours for the shortest to 37 hours for the longest. In this problem, the computer was caused to evaluate a stability factor for each point. When this stability factor indicated that accuracy in computations might suffer, the increment in the independent variable was halved. When, on the other hand, the stability factor indicated that larger steps might be used with relatively little loss in accuracy, the UNIVAC itself automatically doubled the interval.

Problems D, E, F, G, H, and I are all partial differential equations in which basically new approaches of general interest have been used. They are all in various stages of de-bugging or operation.

Charts I and II show the summaries of the UNIVAC operations on each of the seven problems, broken down into appropriate subheadings. It should be observed that one indicates the total number of hours spent on a problem, and the other chart is a percentage-wise breakdown of activities. Each chart should be used in conjunction with the other, since the variation in total time used is very great -- the smallest using 1.7 hours; the largest using 728.7 hours.

Accounting Problem - In the field of commercial problems a general accounting procedure for a division of a large corporation was developed for

CHART I

PERCENTAGE BREAKDOWN OF UNIVAC ACTIVITIES ON AEC PROJECTS

22 APRIL 1952 - 24 AUGUST 1952

Project	A	B	C	D	E	F	G	H	I	Average
Production	41	37	50	39	65	0	83	9	0	41.5
Copying + Merging Tapes	3	4	1	5	2	2	1	6	76	3.1
Editing	2	2	0	3	1	0	1	0	0	1.7
Testing Routines	14	32*	16	37	13	81	0	59	0	22.4
Corrections	6	6	6	3	4	6	1	12	12	5.8
Reruns due to Problem Changes	8	3	12	1	0	0	0	2	0	6.4
Trouble Time	9	8	8	4	3	2	9	7	12	7.5
Reruns due to Computer Trouble	5	3	3	1	4	0	3	0	0	3.7
Down Time	12	4	4	6	7	8	9	5	0	8.0
Totals	100	100	100	99	99	99	100	100	100	100.1

* Figures for this problem are distorted in favor of Testing Routines because various subsidiary routines are included in this problem.

CHART II

SUMMARY OF COMPUTER HOURS USED ON AEC WORK

22 APRIL - 24 AUGUST 1952

Project	A	B	C	D	E	F	G	H	I	Totals
Production	296.3	130.7	148.1	45.1	44.7	0.0	35.7	3.5	0.0	704.1
Copying + Merging Tapes	23.3	15.4	1.8	6.2	1.6	0.9	0.4	2.1	1.3	53.0
Editing	17.7	6.3	0.0	3.3	0.9	0.0	0.4	0.0	0.0	28.6
Testing Routines	101.9	114.7*	48.5	42.8	9.1	41.7	0.0	22.0	0.0	380.7
Corrections	42.9	22.2	18.3	3.6	3.0	3.3	0.4	4.6	0.2	98.5
Reruns due to Problem Changes	60.9	11.7	35.1	0.9	0.0	0.2	0.0	0.7	0.0	109.5
Trouble Time	62.6	28.3	24.3	4.6	1.9	0.8	2.7	2.5	0.2	127.9
Reruns due to Computer Trouble	35.5	12.2	8.4	1.6	3.1	0.2	1.3	0.0	0.0	62.3
Down Time	87.6	15.8	11.8	7.2	4.6	4.3	2.2	1.9	0.0	135.4
Totals	728.7	357.3	296.3	115.3	68.9	51.4	43.1	37.3	1.7	1700.0

* Includes testing time on subsidiary routines.

the UNIVAC SYSTEM. The procedure was based upon 1300 transactions which formed the input to the Computer, and which were then used to produce a preliminary ledger, final ledger, balance sheet, detail of selling and administrative expense, and the statement of income. In order to produce the ledgers, the transaction items were sorted by account number in ascending sequence. The sorted transactions were then merged with the account headings and balances to produce a listing by accounts of the month's transactions and thus create new balances for each account. In addition, statement totals were calculated by groups of accounts which were used later to prepare the balance sheet and associated statement. Trial balance figures were computed for sectioning purposes. Totals, sub-totals, and percentages were calculated according to the various statement accounts used by the company during the procedures which prepare the balance sheet and statements to management.

Railroad Freight Problem - Another commercial problem was concerned with the freight movements originating and terminating on the rail lines owned by a particular railroad organization. The initial process computed a listing by each of the current day's transactions. The transactions were then sorted by commodity number and accumulated day by day so that tables could be prepared at the end of the month to show the monthly movement of each commodity. The transactions were also sorted on a day basis by division at the end of the month. The Interstate Commerce Commission Report was also prepared each month. The total volume for this problem is 8,000 items per day of which a sample input of 2,000 items was used for the demonstration runs.

Life Insurance Problem - A third commercial problem which has been prepared for the UNIVAC SYSTEM and run on one of the installations at the Eckert-Mauchly plant involved a large life insurance activity. Of particular interest in this problem is the fact that the routines used on the UNIVAC reproduced exactly the work presently being performed by punched card equipment. The procedures developed in this way did not, therefore, take full advantage of the potential ability of the UNIVAC. However, there were numerous checks and tests built into the routines that are not possible with the punched card equipment and several additional fields of information were carried with each policy which could not be carried on a single punched card. The work represented a monthly cycle of work performed in the Actuarial Division of the company. Approximately 90,000 monthly transactions in the form of detail cards were transcribed by the present Card-to-Tape Converter. These cards were then processed by the UNIVAC to produce:

(1) An edited policy item file,
(2) A set of check totals, and
(3) The output in tabular form by use of suitable editing routines.

The totals have been checked digit by digit with the equivalent work done by the punched card equipment. There was not one discrepancy which can be attributed to the operation of the UNIVAC SYSTEM. Another file of punched cards was also transcribed by the Card-to-Tape Converter which

included approximately 80,000 cards. All cards transcribed have been checked out and of this total of approximately 170,000 cards, only 13 corrections were required. In order to prove out the routines involved and to do the production running on the first 70,000 cards, including demonstrations, 97 hours of UNIVAC time and 30 hours of Card-to-Tape time have been used.

Such a problem as that just described points out the very important single factor in commercial computation that, where dealing with numerical quantities representing dollars and cents, no errors in any quantity can be tolerated. In contrast, many statistical problems can tolerate random errors of a statistical nature. Such a problem as described above, however, proves error-free handling from start to finish if, as in this case, every balance and total checks identically with previously obtained data by other means.

Stock Control Problem - One of the logistical applications of the UNIVAC is a Stock Control problem for a government agency. In this problem, statistical rates of part replacements during overhauling and maintenance cycles are kept by the stock control point, and are applied against the planned maintenance and overhauling schedules of each station to produce the number of such parts needed in the next quarter. Each station supplies a stock inventory record which is processed against the computed requirement to determine the stock level of the station area. As far as is possible adjustments are made within the system by shipping stock from areas with excesses to areas with deficiencies. The remaining unsatisfied deficiencies are supplied by ordering. Input data for this problem were received as punched cards comprising a selected group of about 300 stock numbers of a particular component. By use of the Card-to-Tape Converter these cards were prepared for UNIVAC operation. From this input data the redistribution pattern is determined and the quantities to be ordered are computed according to geographical sections.

Performance Record

In discussing the performance record of the UNIVAC SYSTEM, the broadest possible interpretation is being placed upon the work performance. The UNIVAC SYSTEM was originally conceived and designed to be a computer intended for mass production in so far as an item as large and expensive as it is can be mass produced. Therefore, the performance of the UNIVAC should be viewed not just as a percentage of down-time, but also in light of its future installation in many locations and operation by many different people outside the sphere of the original design staff. In all respects, it can be said that the original conceptions were sound.

On February 7, 1952, we began for the first time the somewhat fearful task of disassembling, shipping, reassembling and testing out a UNIVAC SYSTEM. Naturally there were many headaches during the course of the next five months until the customer's operators and maintenance man took over and we have learned through hind sight many ways to avoid and lessen these headaches. We have, however, satisfactorily completed the testing out and made complete delivery of a UNIVAC SYSTEM to a point outside our plant.

This system is now completely in the hands of the customer and is continuing to give very good performance records. Considerable planning went into the actual physical moving operation and the consequent engineering tests. The continued satisfactory operation not only verified that planning but also the training programs by which maintenance men, operators, and programmers were prepared for their tasks. We are continuing to study these problems in the hope of further improving the effectiveness of our solutions as well as to shorten the time required to perform them.

In the field of programming and problem analysis we have had additional experience which has also borne out the original conceptions of the UNIVAC SYSTEM. Several prospective customers have analyzed their own problems and have completed their own programming and coding. This work was then run on one of our computing systems. Not one, but several groups of people, not associated with Remington Rand, have already produced programs for the UNIVAC. It is satisfying to know that our method of problem analysis can be taught with ease to the customer, and we are sure that the customer derives great satisfaction from seeing the results of his own study used on the computer.

The first UNIVAC SYSTEM produced was delivered to the Census Bureau. In the December, 1951, paper mentioned above, we predicted that much of the down-time recorded against this first system would be eliminated in later systems because so much of it could be attributed to failures which were designed out of the system. The records on not only system No. 1, but also systems Nos. 2, 3, and 4 amply bear out our earlier hopes. Figure 7 is a bar graph showing the monthly percentages of down-time for system No. 1. The slight rise in March 1952 marks that point when the Census Bureau maintenance personnel took over from the Eckert-Mauchly personnel. At that same time we introduced several improvements in the equipment and gave additional training. As it now stands the Census engineers call on Eckert-Mauchly engineers when they have difficulty diagnosing trouble. It is natural to expect such a jump under these conditions and we feel highly gratified that the jump was so small. Figure 8 shows the percentage of scheduled maintenance time for system No. 1.

Figure 7 showed two peaks in July and September 1951, while scheduled maintenance time (Figure 8) for the same two months was low ; in contrast, August and October 1951 had more scheduled maintenance time and proprotionately less non-scheduled maintenance time. During these two months the scheduled maintenance time was extended so as to allow for the engineering staff to incorporate design changes. In each case the non-scheduled maintenance percentage responded by decreasing. What has been attempted is to maintain enough scheduled maintenance time so as to reduce the non-scheduled maintenance time to a minimum, since the non-scheduled time is a nuisance to both user as well as engineer. It is also worth noting that the UNIVAC SYSTEM No. 1 is the first model, there having been no previous breadboard model built. It, therefore, has been for the most part the proving ground.

Figure 10 shows the percentage of non-scheduled maintenance time based on a week of a 168 hours for UNIVAC SYSTEM No 3. The average for system No. 1 is about 10 percent while that for No. 3 is about 5 percent. Figure 11 shows the scheduled maintenance time for system No. 3.

Our experience with system No. 2 was not of sufficient duration to collect the same amount of data as has been given for systems Nos. 1 and 3. As soon as system number two passed the "Acceptance Test" the Computer was dismantled and removed to its permanent location. However, we have received extremely favorable comments concerning its operation in the new location. It appears to be running about the same amount of down-time as No. 3, using the customer's maintenance group.

To summarize the maintenance problem for the UNIVAC SYSTEM, we feel compelled to give great credit to the inclusion of adequate error circuits. In the first place the error circuits in the UNIVAC cause the Computer to cease further operation which thus prevents the propagation of an error. In addition the error circuits being so numerous are able to lead a maintenance man rapidly to the source of difficulty. When a construction has reached the complexity represented by the UNIVAC Central Computer, isolation of the trouble geographically and logically becomes an appreciable part of the time required for complete remedial action. Only through the inclusion of many check points throughout the Computer system has the non-scheduled maintenance time been kept so low. A further dividend from this design policy is, of course, the guarantee to the user that results obtained have an extremely high statistical chance of being correct.

On August 22, 1952, system No. 4 was given its first acceptance test and has passed it with flying colors. Therefore, beginning as of this date new data will be collected on this system and experience so far leads us to estimate that it will at least equal and very likely better the records achieved by its predecessors. Still later computers are, at present, in various stages of test and construction.

Acknowledgment

All of the various phases of UNIVAC discussed in this paper are the result of the efforts of many different people each of whom has contributed toward the ultimate successful operation of this equipment. It is impossible to acknowledge individually all the credits that are due. Let this, therefore, represent an overall acknowledgment of all the technical and engineering personnel that contributed toward the UNIVAC SYSTEM. Particular acknowledgment is extended to Joseph D. Chapline, Jr., for editorial assistance in preparing this paper.

Fig. 1

Univac System
Showing Central Computer, four
Uniservos, Supervisory Control
and Printer Dolly.

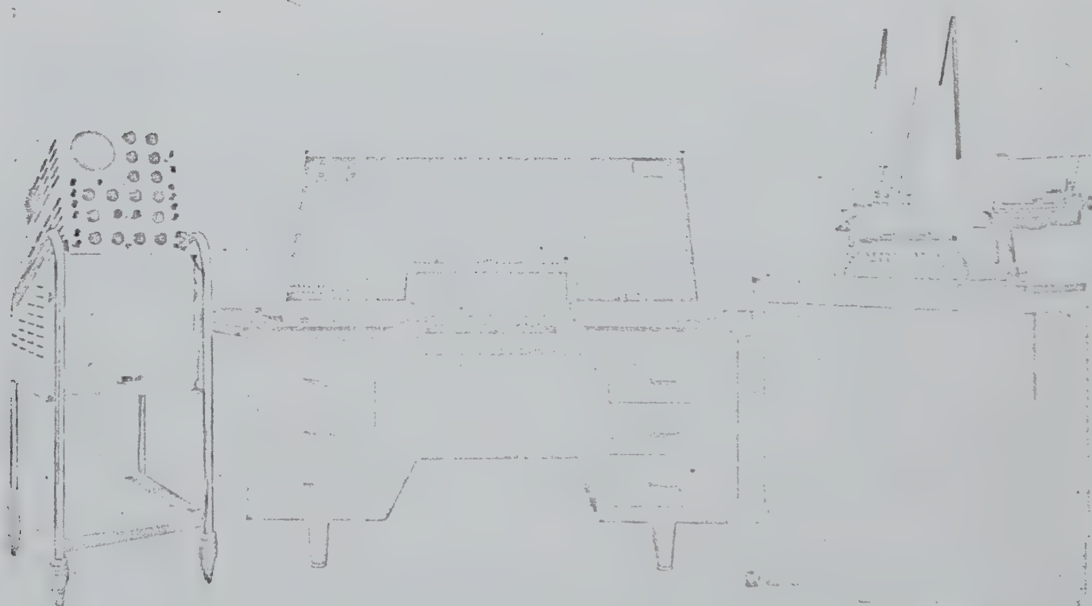

Fig. 2

Supervisory Control Console with
Printer Dolly and 'Scope at sides.

Fig. 3
Unityper with
Keyboard in foreground and tape
recorder in rear.

Fig. 4
Card-to-Tape Converter.

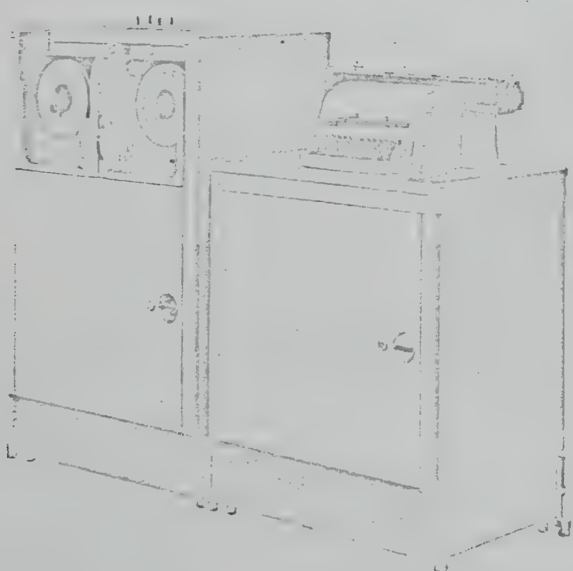

Fig. 5
Uniprinter showing tape reader on left and typewriter dolly on right.

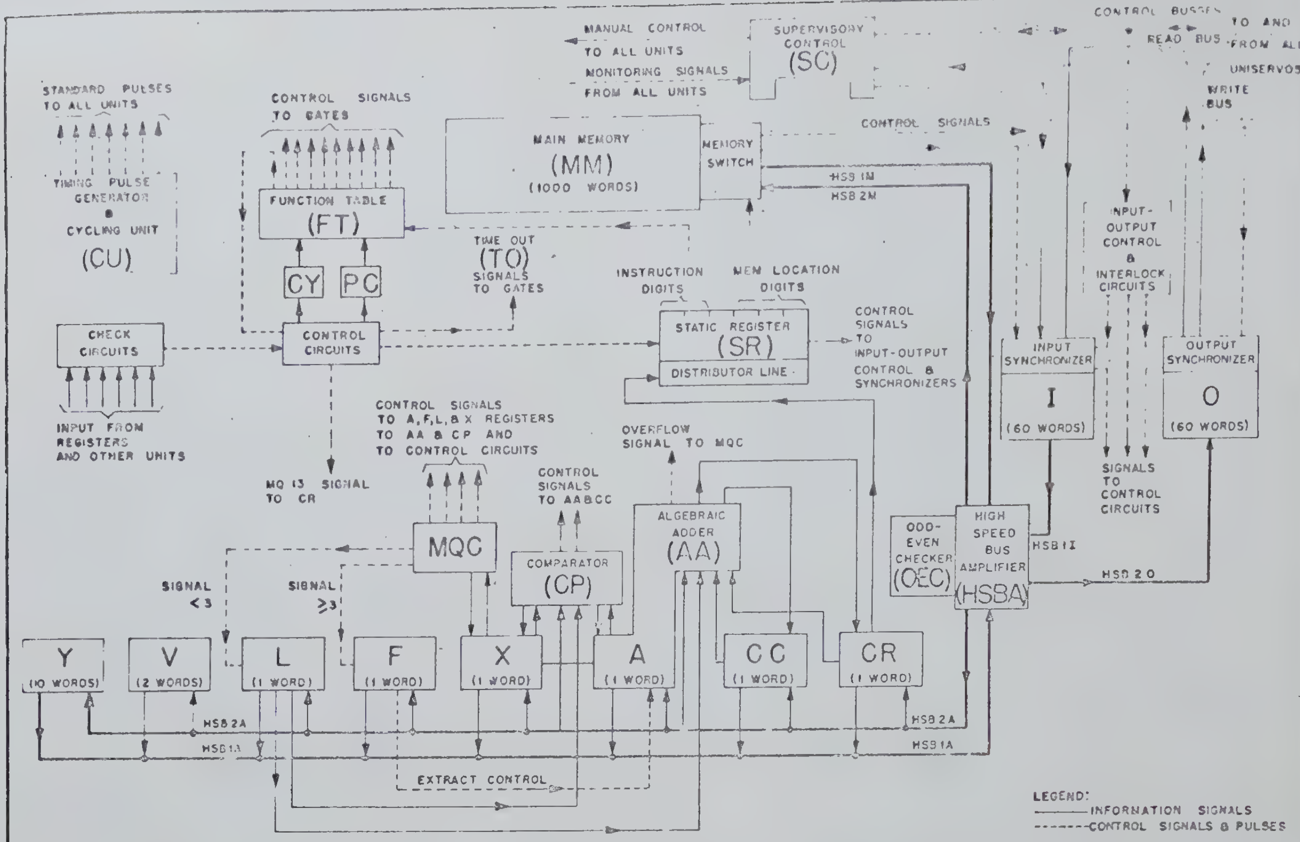

Fig. 6

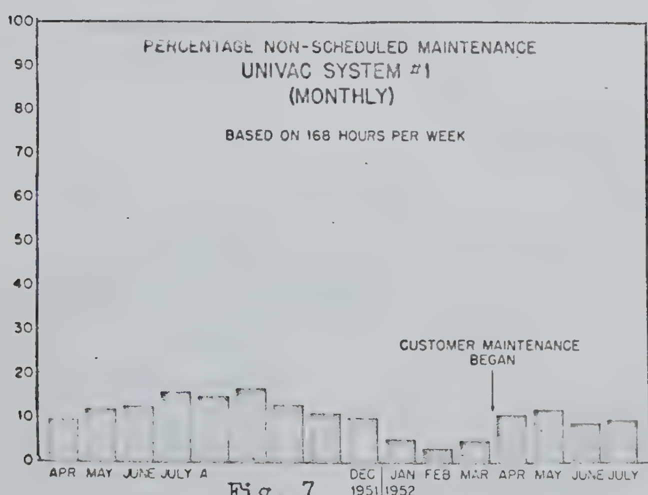

Fig. 7

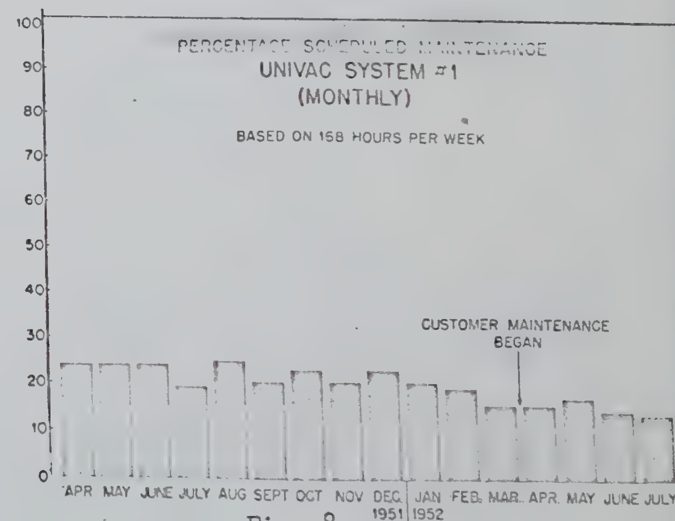

Fig. 8

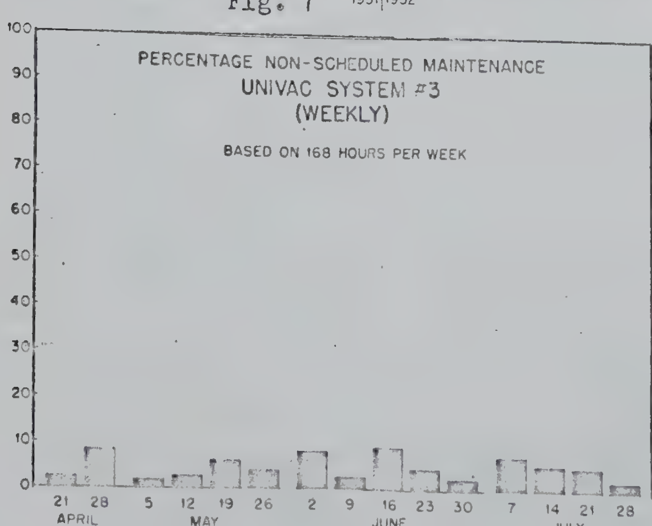

Fig. 9

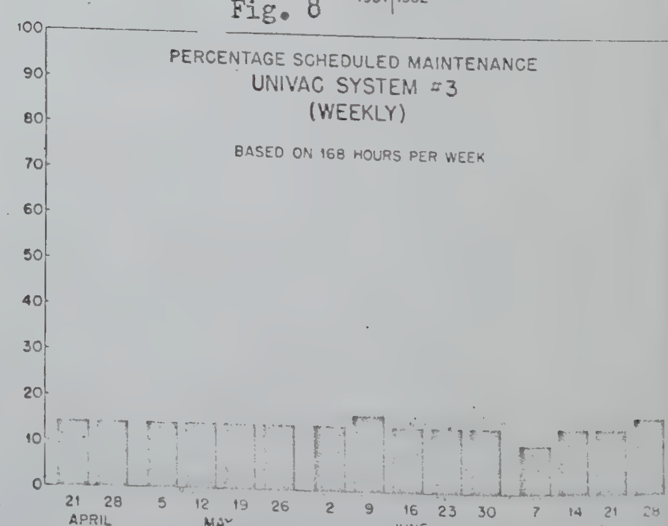

Fig. 10

AN AUTOMATIC CRUISE CONTROL COMPUTER

FOR LONG RANGE AIRCRAFT

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This paper presents a qualitative discussion of present manual cruise control techniques and a proposed automatic cruise control system for long range military aircraft. A mechanization of the cruise control computer and its operation are described, and a comparison of the automatic system operation with current manual techniques is presented. Although the application of the cruise control computer to long range military aircraft in particular is discussed, the principles in general would apply to long range commercial aircraft as well.

The continued increase in range requirements for large military aircraft has accentuated the importance of maintaining a high level of operating efficiency at all times. Of particular importance are the increased requirements placed on long range cruise control techniques in order to obtain maximum range. At present, flight personnel control the power plant-airframe combination to obtain maximum range during cruising flight by adjusting the power settings according to precomputed data obtained from cruise control charts. These charts list the power settings to be used in order to realize maximum range under various operating conditions, such as gross weight, altitude, and wind conditions. The power settings, of course, must be periodically adjusted to account for changes in these operating conditions.

Cruise control charts can be prepared from theoretical calculations or from flight test data. While those prepared from flight test data are more realistic, the cost and time expended in their preparation are tremendous. In either event, the preparation of the charts is usually based on the establishment of ideal airplane duration characteristics. Figure 1 shows the variation in duration characteristic with altitude, for a turbojet airplane. In general the duration characteristics of all airplanes have a similar form regardless of the type of powerplant installed in the airplane. The cruise control information obtained from these curves is shown more clearly in Figure 2. Here a typical characteristic for an airplane of a given gross weight and operating at a particular altitude is reproduced. If the power settings are adjusted to give operation at "A", maximum endurance will be realized. Whereas power settings for operation at "B" would allow maximum range to be realized. In addition to the duration characteristics, data from specific fuel consumption charts, speed-power charts, propeller efficiency charts (in the case of reciprocating engines), and others, are required in the preparation of the complete cruise control charts.

A very serious limitation to the use of these charts is the fact that any adverse operating condition (such as icing, enemy attack damage, malfunctions of

the powerplant or flaps, etc.) makes the information in the charts in gross error at the very time it is needed most. Additional disadvantages associated with the cruise control charts include the necessity of periodic manual adjustment of the power settings, the complexity of the charts with the attendant possibility of error, and the large number of charts required to cover normal operating ranges.

An automatic cruise control system offers a simple solution to these problems. It would eliminate the need for cruise control charts and would also eliminate many of the manual operations required in present cruise control techniques. The operation of the automatic system can be explained with greater ease if the airplane range performance characteristic, shown in Figure 3, is used as reference. This range characteristic can be obtained from the duration characteristic of Figure 2 by plotting the ratio of airspeed to fuel flow as a function of rpm corresponding to the fuel flow.

The form of the range performance characteristic, shown in Figure 3, exhibits the peak required for successful application of optimalizing control to a system. The principles of optimalization control have been developed and proven by Dr. C. S. Draper and Dr. Y. T. Li at M.I.T., and the results of their work have been published by the A.S.M.E. in a paper entitled "Principles of Optimalizing Control Systems and an Application to the Internal Combustion Engine". The operation of the cruise control computer discussed in this paper is based on these optimalizing principles.

The operation of the automatic cruise control system shown in Figure 4, can be explained briefly in the following manner: the cruise control computer continuously monitors the airspeed and fuel flow signals and computes their ratio as the range parameter - - miles per pound. By optimalizing control, the computer causes the engine or turbo rpm to be slowly varied as a function of this range parameter. This rpm variation is constant with respect to time and as long as the range parameter is increasing, the rpm time rate of change is not altered. When the rpm variation causes the aircraft to pass the peak of the range performance characteristic and the miles per pound signal starts to decrease, the computer causes the rpm time rate of change to reverse so that the peak of the performance characteristic is again approached. Thus the automatic cruise control system is designed to control the rpm so that the range parameter approaches and oscillates slowly about the peak of the range performance characteristic.

For discussion purposes only, the computer will be assumed to be installed in a jet-powered airplane that is characterized by the range performance characteristic shown in Figure 3, and the initial power settings result in operation at the indicated point. A schematic diagram of the computer mechanization is shown in Figure 5, where a conventional relay servo can be utilized to perform the indicated division. The arrows in the relay coils indicate the direction of contactor motion when the signal in that coil is dominant. The contactor positions shown in Figure 5 indicate that the signals on the two differential relay coils, "A" and "B", are about equal, and the latching relay is causing the throttle to be slowly advanced and therefore the engine rpm to be increased.

Under the above operating conditions the miles per pound signal fed to coil "A" of the differential relay will be increasing. As the miles per pound signal increases, the differential relay contactor oscillates between positions one and two and intermittently applies excitation to the D.C. motor to drive the potentiometer wiper in a direction to increase the signal on coil "B" of the differential relay. Thus, as long as the miles per pound signal is increasing, a reference

signal is maintained on coil "B" that is equal to, or slightly less than, the miles per pound signal on coil "A".

When the rpm is increased to the point that the range performance characteristic peak is passed, the miles per pound signal starts to decrease. But the signal on coil "B" will remain constant at a value equal to or slightly less than the maximum value which the miles per pound signal reached in passing the peak of the range performance characteristic. When the decreasing miles per pound signal allows the reference signal on coil "B" to dominate, the differential relay contactor is moved to position 3. In this position excitation is applied to the latching relay coil and to the time delay relay. The actuation of the latching relay causes the time rate of change of rpm to be reversed, thus causing the system to again approach the peak of the range performance characteristic. The time delay relay is necessary because of the time lag of the power plant-airframe combination that occurs between an abrupt change in rpm and the resultant change in the range parameter--miles per pound. After this time delay, excitation is applied to the D.C. motor to cause the reference signal on differential relay coil "B" to be eliminated by driving the potentiometer wiper past the potentiometer excitation terminal to the ground terminal. This causes the differential relay contractor to abruptly move from position three to position one and the motor continues to drive the potentiometer wiper until the reference signal on coil "B" is equal to or slighly less than the slowly increasing miles per pound signal on coil "A". Thus the system is ready to start another cycle of operation.

The most important advantage of an automatic cruise control system is the fact that the effects of any adverse operating conditions are included automatically since the actual power plant-airframe combination is an integral part of the system. A qualitative discussion of the effect of some adverse operating condition, such as wing icing, upon the range performance of an airplane will be presented with the aid of Figure 6. The upper curve in this figure represents the performance characteristic during ideal operating conditions, whereas the lower curve represents that particular characteristic which includes the effect of wing icing. If the flight personnel were adjusting the power settings according to data from cruise control charts, these settings would be adjusted to give operation about point A. But operation with these power settings would not allow the maximum miles per pound to be realized as shown by the lower curve. However, if an automatic cruise control system were controlling the power settings, then operation would be about point B--the peak of the actual range performance characteristic. Thus by continually seeking the peak of the actual performance characteristic an automatic cruise control system would result in more miles flown per pound of fuel consumed. While the information in Figure 6 is not to scale, it can be used to illustrate the operation of an automatic cruise control system during some adverse flight condition and the resultant gain in range over manual cruise control. The gain in range, of course, increases as the difference between actual and ideal flight conditions increases.

It should be pointed out that the computer mechanization shown in Figure 5 contains only the basic operating components. A practical mechanization would require smoothing of the airspeed and fuel flow signals as well as providing limits on the airspeed and rpm reduction. In addition, provisions could be included for biasing the airspeed signal to account for wind conditions. An important factor to be considered from the economic standpoint is the sharpness of the range performance characteristic. As the peak of this characteristic flattens out, the gain in range realizable with an automatic cruise control system decreases. However, the ideas for a cruise control computer, as described

in this paper, have had sufficient merit to warrant the establishment of an Air Force development program for the construction and flight test of a prototype unit. The test results of this program should be available in approximately one year.

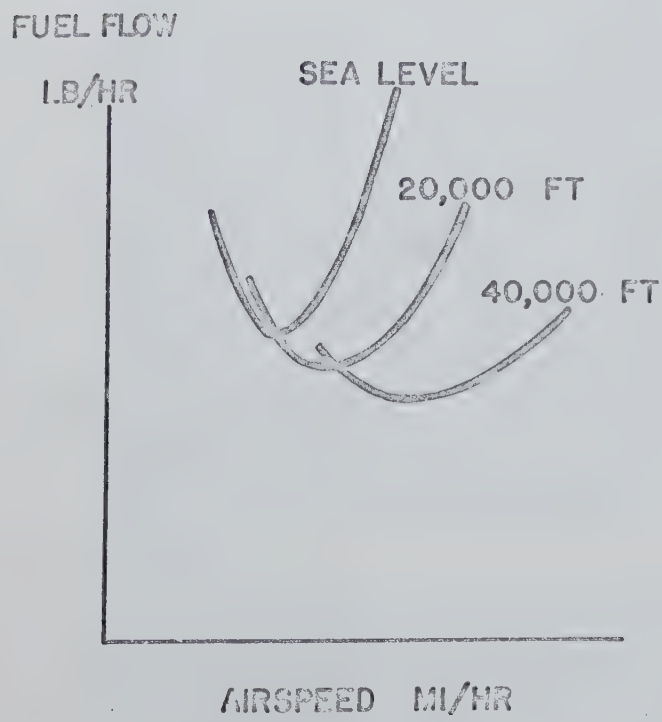


FIGURE 1 - Turbojet Duration Characteristics.

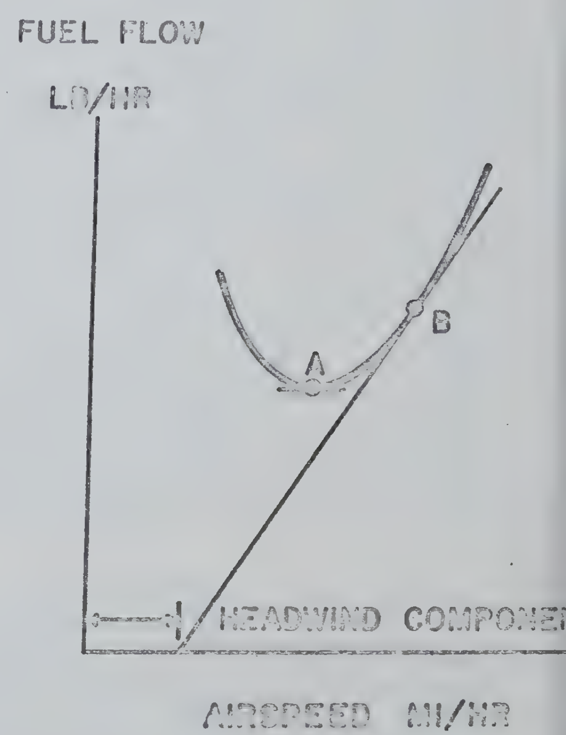


FIGURE 2 - Typical Duration Characteri

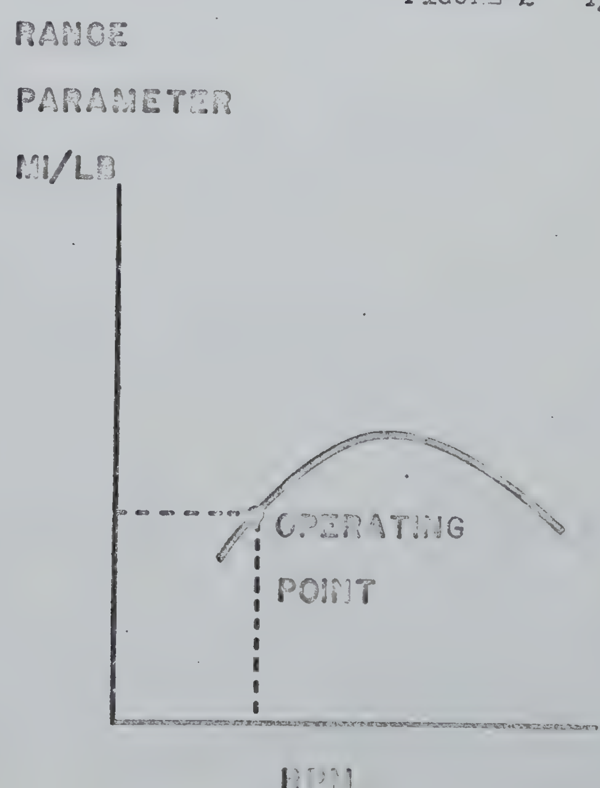
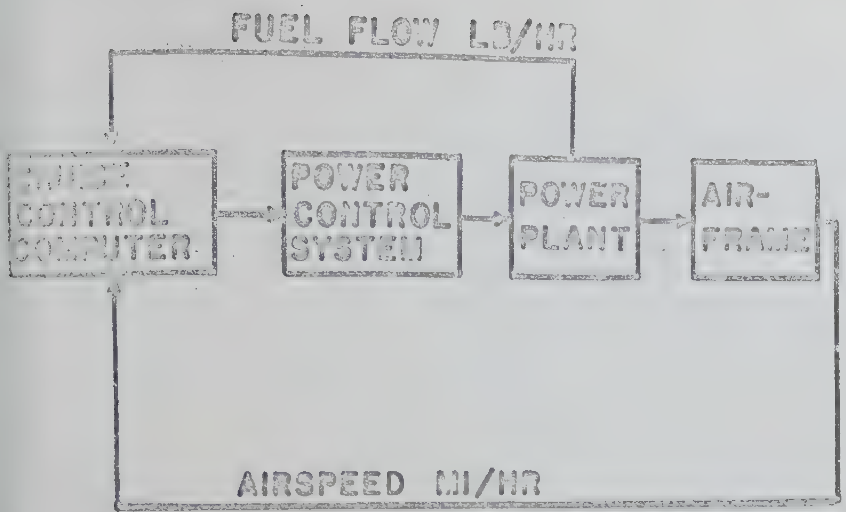


FIGURE 3 - Range Performance Characteristic



URE 4 - Block Diagram of the Automatic Cruise Control System.

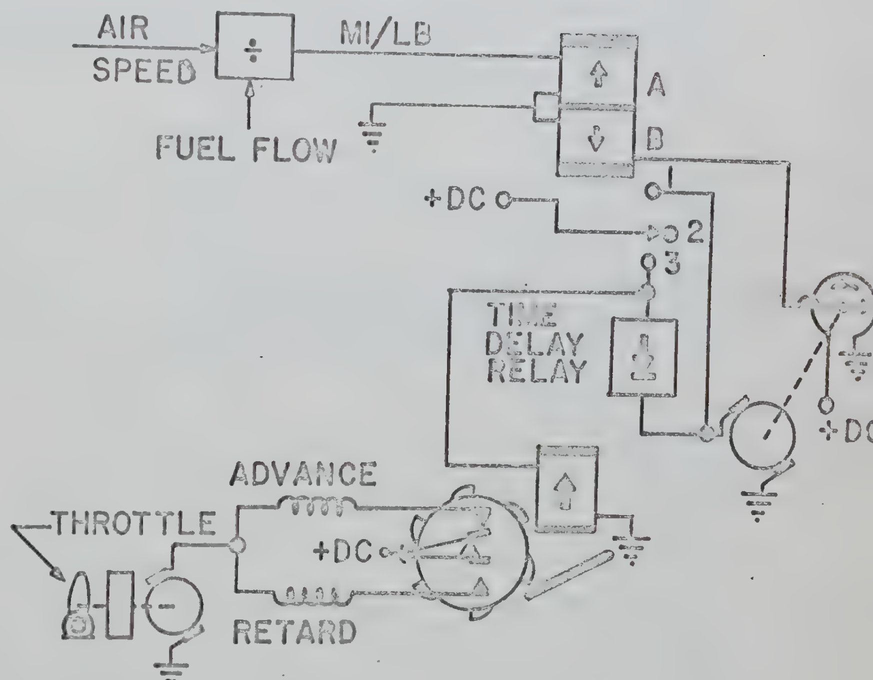


FIGURE 5 - Schematic Diagram of the Cruise Control Computer.

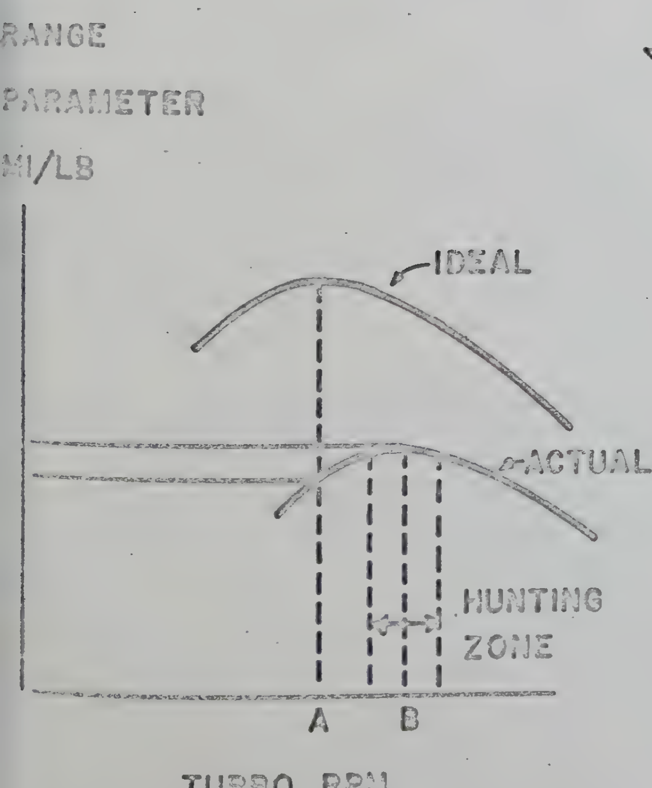


FIGURE 6 - Automatic vs. Manual Cruise Control

A STABILIZED ELECTRONIC MULTIPLIER

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Introduction

Many people engaged in the development of precision analog computing equipment have concluded that the two most useful computing circuit elements are a stabilized d-c amplifier and a high-speed precision switch. The first requirement is met by a circuit disclosed by Goldberg.[1] A method of stabilizing a large number of d-c amplifiers with a single pulse amplifier was first reported by Ingerson.[2]

A variety of electronic switches have been described in the literature. Most provide the necessary speed but, to the authors' knowledge, few provide the accuracy and drift-free operation required for precise computing. The authors have used a simple but adequate voltage switch in a time-division multiplier[3]. Goldberg[4] has described a precision current switch; although this switch meets all operational requirements, it is somewhat elaborate and is restricted to unidirectional currents.

This paper describes a time-division multiplier employing stable, precise voltage switches. Stabilization, by reducing drift, provides increased accuracy and repeatability; by eliminating the need for manual balancing and alignment, it affords greater operating convenience, particularly when a large number of multipliers are used in a single installation.

Contrary to earlier expectations, the stabilized multiplier is simpler and probably more reliable than the unstabilized multiplier reported by the authors in 1951.[3] An important feature of the multiplier is its ability to recognize and to signal overdriven inputs, an overloaded output, or a component malfunction; the complete failure of any part or the out-of-tolerance failure of any tube or resistor, except for a few wire-wound resistors, is immediately made known to the operator by visual or audible means.

This stabilized multiplier, in its present form, uses eighteen vacuum tubes, none of which requires selection. In the current stage of development, its accuracy is to within 0.1%. Changes in calibration and drift from day to day are negligible; accuracy and repeatability are maintained even with changes in vacuum tubes. The frequency response of the multiplier, measured at its output, is flat to about 200 cycles per second.

Theory

Although the basic method of time-division multiplication is not new,[3-4] an explanation of the process will be repeated. The algebraic product of two voltages is formed by averaging several cycles of a quasi-rectangular waveform; as shown in figure 1, the duration and amplitude of alternate portions of the waveform are functions of the input variables. The amplitude of the first portion of each cycle is Y and its duration is $T_1 = K/(Z - X)$ second; the second portion is $-Y$ for $T_2 = K/(Z + X)$ second; the average value is $Y(T_1 - T_2)/(T_1 + T_2) = XY/Z$. This basic waveform does not actually appear anywhere in the multiplier; however, the same effect may be produced in several ways, one of which will be described.

Figure 2 is a block diagram of a time division multiplier. Timing of the waveform is dependent on input variables X and Z, and is controlled by switch 1, the integrator, and the bistable multivibrator. The multivibrator, which changes from one of its stable states to the other whenever the output level of the integrator reaches e_1 or e_2, actuates switches 1 and 2 in unison. When the output of the integrator reaches e_2, switch 1 is closed and the input to the integrator is:

$$\frac{X}{c} + \frac{Z}{2ab} - \frac{Z}{ab} = \frac{X}{c} - \frac{Z}{2ab} \qquad (1)$$

where a, b, and c are constants. Since the output of the integrator must reverse direction, one requirement in the choice of constants is that:

$$\frac{Z_{min}}{2ab} > \frac{X_{max}}{c} \qquad (2)$$

The output of the integrator then increases linearly with time from e_2 to e_1; the required transition time, T_1, is established by the following equation:

$$K\int_0^{T_1}\left(-\frac{Z}{2ab} + \frac{X}{c}\right) dt = e_1 - e_2 \qquad (3)$$

where K is the gain of the integrator.

From Equation (3), it follows that, since X and Z may be assumed constant over the interval,

$$T_1 = \frac{e_1 - e_2}{K\left(\frac{Z}{2ab} - \frac{X}{c}\right)} \qquad (4)$$

Similarly, when e_1 is reached, switch 1 is opened and the integrator output decreases linearly with time from e_1 to e_2 establishing the time T_2 by

$$K \int_0^{T_2} \left(\frac{Z}{2ab} + \frac{X}{c} \right) dt = e_1 - e_2. \tag{5}$$

Therefore,

$$T_2 = \frac{e_1 - e_2}{K\left(\frac{Z}{2ab} + \frac{X}{c}\right)} \tag{6}$$

The output of switch 2 is $-Y/d$ during the interval T_1 and zero during T_2; thus the average input to the output amplifier and filter is

$$(Y/2kd) - \frac{(Y/kd)T_1}{T_1 + T_2} = \frac{Y}{kd}\left[\frac{1}{2} - \frac{T_1}{T_1 + T_2}\right] = \frac{ab}{kcd}\left[\frac{XY}{Z}\right] \tag{7}$$

The scale factor of the output amplifier is such that the output voltage is XY/Z.

The frequency or repetition rate of the quasi-rectangular wave is

$$f = \frac{1}{T_1 + T_2} = \frac{Kab}{e_1 - e_2} \cdot \frac{(Z/2ab)^2 - (X/c)^2}{Z} \tag{8}$$

With Z = +100 volts, this frequency varies from 15 KC for X = 0 to 10 KC for X = + 100 volts. It decreases rapidly with Z, and consequently, in common with other time-division multipliers, there is a limitation imposed upon the minimum value of Z which may be used in problems in which good filtering of the carrier frequency is required. In problems requiring both a wide range in Z and good filtering, a circuit employing a multiplier with two Y-sections may be used.

Switch 1 of figure 2 is shown in more detail in figure 3; it consists essentially of a stabilized d-c amplifier having two alternately switched feedback impedances. During the positive portion of the input from the multivibrator, V3A conducts disconnecting R_{01}; simultaneously, V3B is cut off, and conduction through V2 closes the feedback path through R_{02}. Similarly, during the alternate period, the feedback path is maintained through R_{01}. The output voltage is taken from the junction of V2 and R_{02}; when V2 is on and V1 off, the output voltage is precisely equal to $(R_{02}/R_i)Z$. When V1 is on and V2 is off, the output voltage is zero since the junction of R_i, R_{01} and R_{02} is maintained at ground potential by the d-c amplifier.

When this type of switch is used to supply the resistive input of a d-c feedback amplifier, the chief sources of error are due to the stray capacitances of V_1, V_2, and V_3, and to the winding inductances of the wire-wound resistors, R_{01} and R_{02}. The effect of stray capacitance is minimized by the use of low values of resistance for R_{01}, R_{02}, R_1, R_2, and R_5; winding inductances are compensated by the use of small shunting capacitors.

In order to achieve good filtering of the output without inducing excessive phase shift at low frequencies, it is necessary to supply an RC filter from the output of switch 2. Although the output impedance of the closed switch is quite low, the impedance of the opened switch, compared to that of the RC filter, cannot be made negligibly small. As a result, the transadmittance of the input network is not constant but is a function of β $(= T_1/ T_1 + T_2)$. This partial filter together with the output amplifier and the remainder of the output filter are shown in figure 4(B). The error caused by the finite output impedance can be compensated completely by using an identical RC network between the output of switch 2 and the integrator; thus, $C_1 = C_3$, and $R_1 = R_2 = R_6 = R_7$. $R_4 C_2$ is made equal to $\left[R_1 R_2/(R_1 + R_2) \right] C_1$ to retain true integration of the applied voltages.

The design of the output filter for a time-division multiplier is made difficult because the intended use of the device is not always known. If the output is to be integrated, little or no filtering is required. On the other hand, if the output is to be connected to some other non-linear circuit, very good filtering may be required to prevent an undesirable d-c off-set; this is particularly true if one multiplier supplies another operating at or near the same repetition rate. Since too little filtering may cause gross errors, a small amount of phase shift at signal frequencies must be tolerated in the general design and a compromise between carrier attenuation and signal phase shift must be made. The three section filter used has a transfer function

$$G(p) = \frac{(0.1 \tau p + 1)}{(\tau p + 1)(\tau^2 p^2 + 0.5 \tau p + 1)} \tag{9}$$

where

$$\tau = 10^{-3} \text{ second} \tag{10}$$

The attenuation and phase shift curves of this filter, figure 5, show that the attenuation is 57 db at 10,000 cps, that the phase shift is 16 degrees at 200 cps, and that the response is essentially flat to 200 cps.

The operation of the complete multiplier, including the switches and the sweep generator, is stabilized against drift merely by stabilizing the four d-c amplifiers; the method used is due to Ingerson[2] and consists of sampling the error voltage at the summing point of each amplifier periodically (approximately 3 times/second), of amplifying the error voltage by an a-c amplifiers, synchronously rectifying the amplified error voltage, and applying it to a low pass filter which is connected to the d-c amplifier in such a manner as to reduce the original error voltage. This method reduces effective amplifier drift by a factor of about 500:1. The output pulses of the a-c amplifier,

which are proportional to the error voltage at the summing point of the d-c amplifiers, are used to indicate excessive summing point error (approximately 0.005 volt) due to an overloading or a malfunction of the multiplier.

Results

A few of the basic waveforms are illustrated in figures 6 through 8. Figure 6 shows the output of the Y-switch when both X and Y are constant; the repetition rate is about 15 KC. Figure 7 shows the effect on the amplitude of varying Y. Figure 8 illustrates the operation of the integrator.

Figures 9 through 11 give a rough measure of the multiplier performance. Figure 9 shows the output of the multiplier when Y is constant and X is a hundred cps square wave; in figure 10, the X and Y inputs have been interchanged. Figure 11 shows the result of squaring the quantity A sin $200\pi t$.

Table I summarizes the multiplier characteristics; the multiplier is still undergoing development and its performance is expected to improve.

Table I

Tentative Specifications
Stabilized Electronic Multiplier

Input Impedance	250 K Ohms
Output Impedance	20 Ohms or less
Input Voltage Ranges	$\pm$ 100-v (except Z which is always positive)
Output Voltage Range	$\pm$ 100-v
Static Accuracy	To within 0.1% of full scale
Maximum Frequency for Full Scale Operation	500 CPS
Frequency Response	
Amplitude	Flat to about 200 CPS 3 db rise at 1000 cps
Phase Shift	16 deg. at 200 CPS 0.7 deg. at 10 CPS
Noise (Z = 100-v)	0.1-v, rms, at frequencies above 10 KC

Conclusions

This paper has described a new high speed electronic multiplier for use with analog computers. A particular feature of the multiplier is a precision electronic switch using a stabilized d-c amplifier. This multiplier provides improved static and dynamic performance for analog computer use.

The stabilized switch may be used with other circuits to provide function generation, interpolation, quadrant switching, analog to digital and digital to analog conversion, and miscellaneous analog computer operations requiring high-speed switching.

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3 Baum, R. V., and Morrill, C. D., "A Time-Division Multiplier for a General Purpose Electronic Differential Analyzer", unpublished paper presented at the 1951 National Convention of the IRE.

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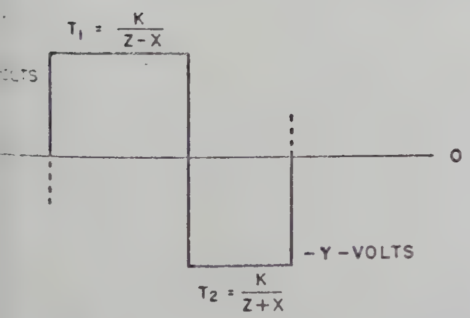


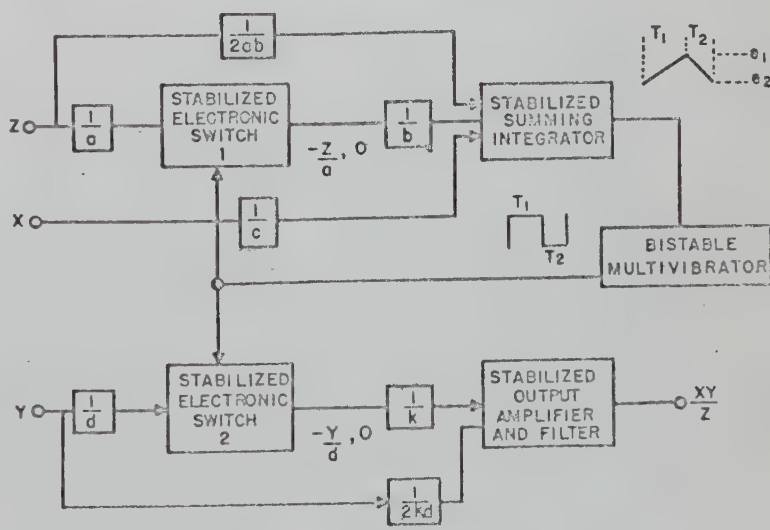
AVERAGE VOLTAGE OVER ONE CYCLE $= \frac{Y(T_1 - T_2)}{(T_1 + T_2)}$

$$= Y\left[\frac{\frac{1}{Z-X} - \frac{1}{Z+X}}{\frac{1}{Z-X} + \frac{1}{Z+X}}\right]$$

$$= \frac{XY}{Z}$$

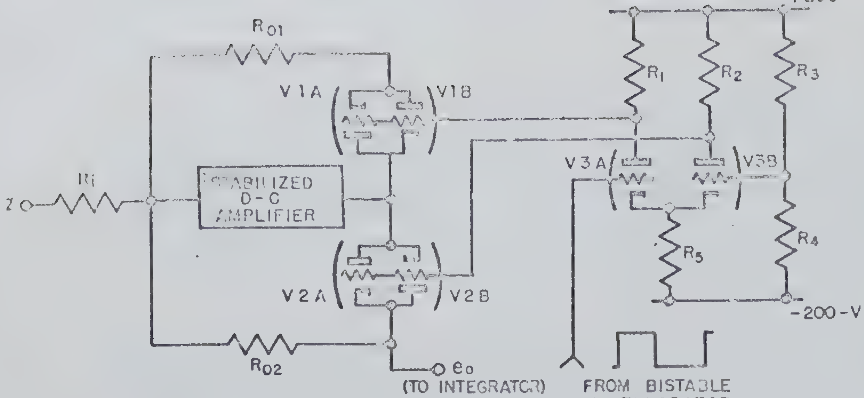
TIME-DIVISION WAVEFORM

Fig. 1



BLOCK DIAGRAM OF A STABILIZED ELECTRONIC MULTIPLIER

Fig. 2

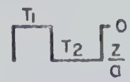


OUTPUT TO INTEGRATOR

$e_0 = \frac{Z}{a}$ $(0<t<T_1)$ Where

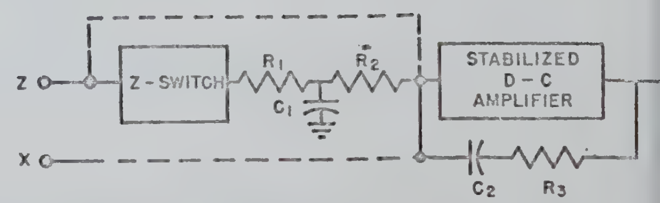
$a = \frac{R_i}{R_{02}}$

$e_0 = 0$ $(T_1<t<(T_1+T_2))$

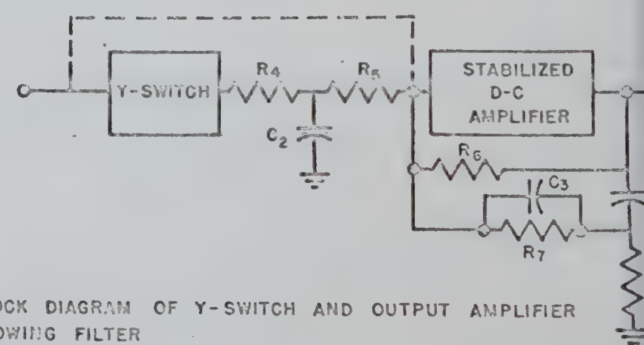


BLOCK DIAGRAM OF A STABILIZED ELECTRONIC SWITCH

Fig. 3

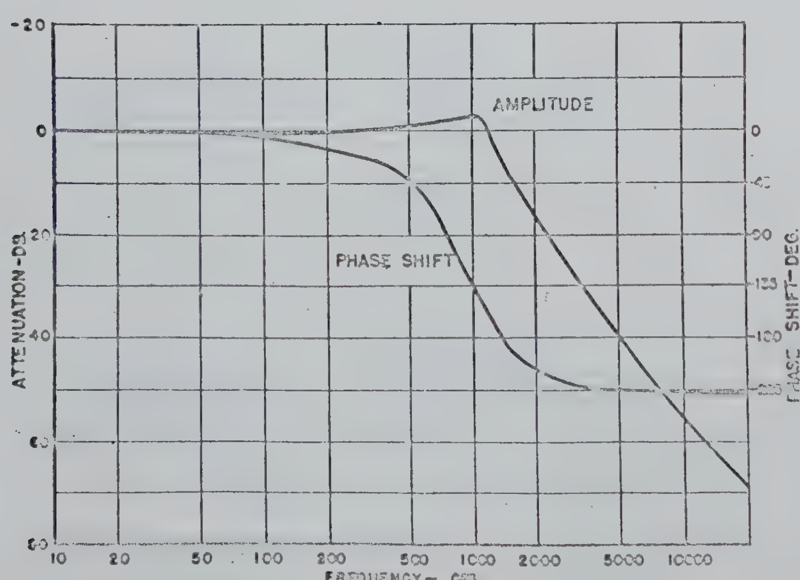


BLOCK DIAGRAM OF Z-SWITCH AND INTEGRATOR SHOWING FIL



BLOCK DIAGRAM OF Y-SWITCH AND OUTPUT AMPLIFIER SHOWING FILTER

Fig. 4

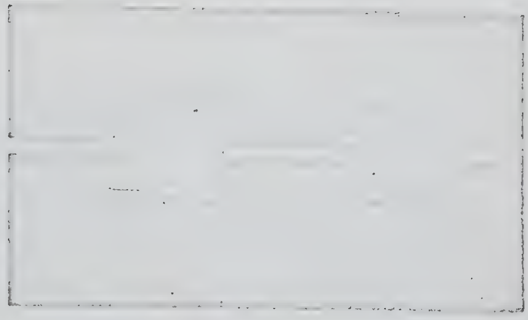


FREQUENCY CHARACTERISTIC OF MULTIPLIER OUTPUT FILTER

Fig. 5

OUTPUT OF Y-SWITCH; WITH CONSTANT VOLTAGE APPLIED

Fig. 6

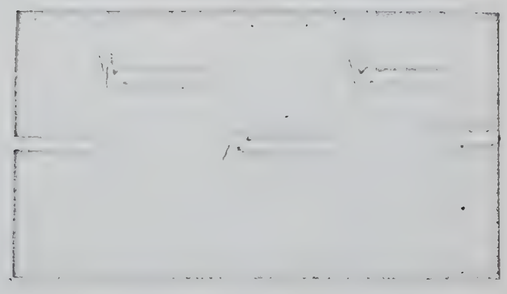


OUTPUT OF Y-SWITCH WITH VARIABLE VOLTAGE APPLIED

Fig. 7

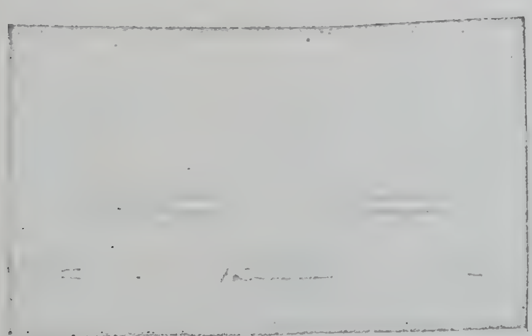
OUTPUT OF ERROR INTEGRATOR

Fig. 8



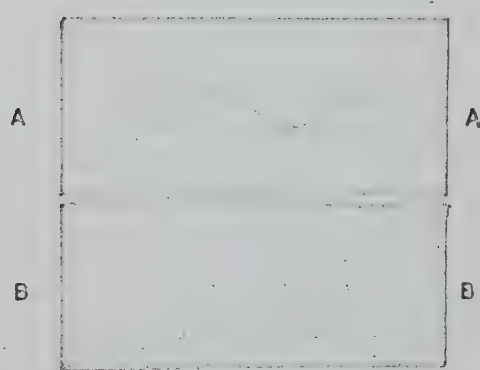
STEP FUNCTION RESPONSE X - CHANNEL

Fig. 9



STEP FUNCTION RESPONSE Y- CHANNEL

Fig. 10



A INPUT TO MULTIPLIER; A sin $200\pi t$
B MULTIPLIER OUTPUT

Fig. 11

HIGH DENSITY DIGITAL RECORDING SYSTEM

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Answer to a Need

Magnetic Recording Applications in Digital Equipment.

The numerous economic uses of magnetic recording today bear witness to the scope and quality of the development in recent years on the media, transducers, kinematics, circuits, and systems involved.

Magnetic recording is already "of age" in several different forms in digital equipment. For example, magnetic drums are widely used for storing moderate quantities of information such as problem input data, function tables, program sub-sequences, and intermediate results. In fact, drums are used wherever random access at medium speed is wanted among a rather limited number of items. Another form of magnetic recording, common where storage is needed for much greater quantities of information to which random access is not required, is magnetic tape. One of its typical functions is that of a funnel or speed-difference compensating device, as between the output of many clerks and a single machine capable of handling their combined efforts, or between several machines and a high-speed printer able to print their total output.

In many of these applications the density of information is not now a problem. Their purposes are served economically by the 50 to 100 and more BITs per lineal inch per track, that are obtained with modern media and heads using techniques already published.

On the other hand, further increase in information density using the same media and heads, has real economic value for the kind of random access memory needed in the newer automatic clerical machines.

RAM Butts Against Density Limit.

Here the amount of information dealt with is prodigious and the required filing capacity is correspondingly vast. Here, access time is the bottleneck because it depends on the size of the filing unit. That, at best, is enormous. And the filing unit's size in turn, depends, among other factors, on the density at which the information is filed. In this relatively new field then, where system performance is gauged by its savings in man-hours, a new importance accrues to the effective density at which digital magnetic recordings can reliably be made and read. In fact, a few tubes more than normally required might well be justified in the magnetic writer and reader attaining greater than normal density with any given head and medium.

Because of our pioneer development of the POTTER RANDOM ACCESS MEMORY - the RAM, that is, with the prodigious digital capacity - we were among the first to reappraise the value of higher density recording in the light of the economics of the newer automatic clerical machines. Under this stimulus we had the good

fortune to arrive at a simple but effective system for increasing digital information density.

The application - even the meaning - of information density is affected by interesting conditions specific to the digital field and to the magnetic recorders used there.

Some Digital Recording Considerations.

Primary Object.

For example, a recording system for digital use differs in object and basic requirements from one for audio.

Its object is relatively simple. It has only to reproduce binary coded information, but with utmost reliability. It must unfailingly indicate the presence of each binary digit or BIT of information, and discriminate between the two values, zero and one. That is all.

Resultant Requirements.

It does not primarily require amplitude linearity, as does audio, nor is it concerned in the same way with introduced noise. Digital recording is, however, concerned with minute probabilities of error and of failure of such error detecting means as may be devised. For example, the waveform distortion could be 30% instead of 3, and the ratio of signal to hum only 15 db instead of 50, but a mere 1% probability of the undetected loss or mutation of as much as one BIT in a billion may be inadmissable.

Density.

Digital equipment is concerned, as we have indicated, with information density. Assuming the closest track spacing permitted by allowable cross-talk, the concern is simply one of lineal density, or BITs per inch, and is related to frequency only through the velocity of the medium relative to the transducer. Frequency, dictated by application requirements, may be less than 1 kb (kilo-BITs per second, that is) or more than 100 kb, and may be different in playback from the recording rate, but once chosen it is fixed for a particular operation. For that operation then, speed is set at the quotient of the chosen BIT frequency, divided by the lineal BIT density to be used. We coin the rate unit, kb, to emphasize the distinction between rate as applied to transiently starting, shifting, and stopping BITs, and rate as applied to continuously repeated identical cycles. For example, to reproduce binary digits at a rate of 5 kb may require circuits passing up to 15 kc or even 30 kc depending on the system used. Correspondingly, a combination of transducer and magnetic medium that provides audio recording up to say 600 cycles per inch, may reliably store less than 200 or even 100 BITs per inch, depending on the system used.

Figure 1 illustrates playback waveform of a particular sequence of 8 BITs in our system of magnetic recording. We have taken the liberty of referring to its density as high. The two lower oscillograms might be taken to show a system different from that revealed in the upper one - there are obvious differences in detail. However, before getting involved in density as applied to systems and clocking, let us simplify our ideas about density. BITs per inch

is an overall yardstick for the combined performance of transducer, medium, and system.

Lineal Resolution.

Let us factor out the effect of transducer and medium by referring to their combined lineal resolution, as in Figure 2. Here the length, S, is the spread of the playback voltage pulse occurring in the reproduction of unit function recording current.

It will be helpful to observe and remember that Figure 2, like all of our waveform illustrations, refers directly to distance along the medium, rather than to time, as the independent variable or abscissa. Correspondingly, the ordinate unit for playback waveform is actually volts per unit of playback velocity.

For the better magnetic reproducing equipments of today, the shape and length, S, of the step response are determined mainly by the so-called gap effect on playback. They are modified to some extent by fringing effects on both recording and playback, and by effective B-H non-linearity in recording. These effects, in turn, depend on various complex characteristics of head, medium, and recording technique. Any improvements among these factors will reduce the spread, or length, S, independent of the system of intelligence presentation, and so increase density. Conversely, any improvement in system, whereby less units of the length, S, are required per BIT stored, will improve density, regardless of the actual length of the spread.

Let us assign the symbol Lambda to represent the absolute length of medium required for storing each BIT. Then for system appraisal, the relative length, or ratio of lambda to S, is the BIT length measure from which extraneous factors have been eliminated. The smaller the ratio, lambda over S, the higher is the density of the system.

Points of View of System Synthesis.

It is natural to think of the system of representing information in terms of the first translation, that from discontinuous binary code to writer current. At least we can easily be sure the chosen current variations are physically possible. But we still cannot escape the final necessity of determining the corresponding playback waveform, to verify that it retains the essentials for the information's reconstruction by possible circuitry in the reader.

This playback waveform may be constructed from the heuristic current function by superposition, using the playback voltage response of Figure 2 as the indicial impedance, where the form of the latter, as is usually the case, is determined mainly by gap and fringing effects with little influence by B-H non-linearity, and also in the case where writing magnetization varies between positive and negative saturation only, in full steps.

For quick exploration, the playback waveform may be roughly visualized as the derivative of a low-pass transmission of writer current in which discontinuities have been spread out and rounded off. With still less accuracy, and increasing risk of complete ambiguity as lambda over S is reduced, we may conversely imagine writing current as a peculiarly angular integral of any

proposed playback waveform.

The latter technique facilitates the utmost simplification of playback waveform consistent with its deciphering, and permits postponement of the labor of more rigorous verification of its correspondence with physically possible writing current. The relative heuristic value of this approach to system synthesis is an open question, but we have found the approach useful.

System Examples.

Reflecting this latter point of view, we shall use system here to mean basically that of the representation of one, zero and neither, in the playback waveform. For example, a dot and 4 dashes of keyed carrier representing a 1, 5 dashes for a 0, and no signal for neither, would be an absurdly expansive system for representing the three choices. At the other extreme, still referring to playback waveform, a negative pulse for a 0, a positive for a 1, and no signal for neither would be compact but physically impossible with respect to writing current without modification for the general case in which BITs of one kind may outnumber those of the other by an indefinitely increasing margin.

A suitable modification would be the periodic reservation of a number of equalizing BIT spaces, equal to the preceding number of informing BITs, so that the recording current and the magnetization in the medium could be stepped back substantially to neutral under an automatic control. The control would continue to step the recording current up and down in this region for any part of the equalizing interval left, just so the reader could count out the full interval and reopen its output gate synchronously with the reappearance of information. After all this complication, it seems that half of the system's potential information density is lost by the modification that makes it workable. But let us label this one System A for later reference.

An alternative modification which we might label System B, comes closer to achieving the full density capability of a theoretical recorder and medium of infinitely linear response. In this one, as in System A, an equalizing period of N BITs is reserved to step the magnetization back to neutral. However, the occurrence of this equalizing interval is not after every N informing BITs, but only after an excess, N, of informing BITs of one sign over those of opposite sign. If the distribution of BITs is at all random, then as N is increased, the ratio of equalizing space to informing space will rapidly decrease from unity toward zero. The required additional circuitry in both recorder and playback may well be worthwhile for certain applications, if use is made of a head and medium whose combined effective linearity is sufficient to enable the value of N to be as great as say 5 or 10.

In connection with System A, it is recalled that a number of magnetic-equalizing BIT-spaces regularly followed each equal number of informing BITs. It may be of interest to observe that if this number is reduced to unity, we have a writing current pulse system with positive pulse for 1 and negative for 0. The implicit pulse width is about twice optimum, but the packing actually about what the conventional writing current pulse system can do, as may be deduced from Figures 3, 4 and 5.

Self vs. External Clocking.

Implicit in the foregoing discussion of system was the assumption of self-clocking. That is, we required of the information playback waveform the full identification of each recorded BIT, without reference to any other channel or indexing marks. Thus the storage system must provide three separately decipherable states to indicate not only the difference between a 1 and a 0, but also the absence of either, where spaces with no information occur. If, however, a signal is available from a so-called clock channel, recorded and played back synchronously, and indicating by the presence of its signal the location of each BIT in the information channel, the burden on the latter is reduced from discriminating among the three choices 0, 1, and neither, to showing the simple choice between 0 and 1 only. For example, separately clocked information may indicate a 1 by any chosen signal and a 0 by the mere absence of that signal.

Clearly, separately clocked information can be stored at a greater density, in BITs per inch, not counting the extra space taken by the clocking channel itself, than can self-clocking information using the same transducer and medium. Hence, any density comparison between systems is fully significant only when they are alike in respect to clocking or when any differences in this respect is noted. It may be recalled that our system, shown in Figure 1 for both external and self-clocked condition, squeezed the externally clocked information into half the space required for the same information self-clocked.

Whether separate clocking is economic depends on mechanical aspects of the application.

Clocking vs. Mechanical Factors.

In the case of rigid drums having rigidly mounted heads, a high degree of precision is possible in the duplicability of the spatial correspondence between points on different tracks. Also, in deference to speed and eccentricity, non-contact recording is the rule, so the lineal resolution suffers. Because of these two circumstances, the use of a separate clock track has not in itself placed a lower limit on the BIT spacing at which individual BITs may be identified by reference to the separate clock. Furthermore, for the typical drum on which many tracks are provided, the reservation of one separate track for timing sacrifices little capacity percentage-wise. So separate clocking is natural for drums.

Magnetic tapes are another story. When reading a multichannel tape, its traverse under a multiple in-line head can differ in direction by a very small angle from its traverse under the same head during recording. While the size of this angle is kept small in the best tape handlers, it can never be assumed to be zero. So, as the spacing between BITs on a tape channel is reduced, an ultimate limit is reached where correspondence between BITs recorded on two seperated tracks may in reading be shifted more than half a BIT space. At this limit, a clock signal on one track can no longer identify information on the other. In other words, this is a limit on usable density of any information that is not self-clocking.

For example, in a handler holding the tape direction within plus and minus one-half degree, using 1" tape, a central clock channel fails as reference for

outside information tracks at densities greater than about 50 BITs per inch.

Furthermore, with the usual four to six channels for parallel presentation, and especially the single channel used in serial operation, the requirement of a clock channel appreciably reduces the space available for information, and thus reduces effective information density.

Another consideration applies to tapes because of their change in length with temperature, humidity and tension. Maximum lateral density, or crowding of the tracks across the tape, is commonly achieved by the staggering of gangs of heads necessarily separated by their length along the line of tape motion. Under these conditions, the space necessary to allot each BIT along a channel is something over twice the product of the total per-unit change in tape length for all reasons between recording and reading, multiplied by the axial separation between working gaps in the forward and rear gangs, in order to maintain the BIT synchronism required if the forward gang's channels are not clocked independently of those under the rear gang. For example, one inch between gangs and two one-hundredths change per unit length of tape would limit BIT density to less than 50 per inch unless separate clock channels were reserved for each in-line gang - or unless, of course, the recording were self-clocking.

There are, then, more natural applications for the self-clocking system in digital tape equipment where high density is desirable, than in drums for which external clocking is practical even at high density.

The High Density System

Demonstration of Density.

Except for the simplicity of the playback waveforms in Figure 1, there is little concrete evidence of unusual density. We shall try to develop the evidence by comparisons with what we understand to be conventional systems.

This development will start with the illustration of physical facts basic to both conventional and high density systems, and arrive at density limits in terms of the common basis so that these limits can be compared. Because the self and externally clocked reproductions differ from each other in density limits and detail, both in the conventional system and in our high density system, we will actually be developing four density limits. Perhaps we should have referred to four systems: conventional self-clocking, conventional externally clocked, high density self-clocking, and high density externally clocked. But the former two are, at least, both pulsed-writing-current systems and the latter two, notwithstanding their differences, have more in common than high density, as will be shown later. Meanwhile, let us start with the physical basis common to all.

Because short pulses were used in conventional recorders to obtain digital packing, it seems reasonable to investigate the effects on playback voltage waveform or resolution when pulse width is varied. Figure 3 indicates that there is an optimum width, in terms of S, below which amplitude is lost with no further decrease in playback voltage peak separation. For the typical "spread" shape shown in Figure 2 and used as the basis of all our waveform illustrations, this optimum pulse width is one-half S.

Having arrived at the writing current pulse width appearing to give the best resolution, we are interested in finding how close we can pack the pulses, both when they are of like polarity and when their polarity alternates, without losing their identity in the playback voltage waveform. Figure 4 shows the effect on playback voltage waveform when we start packing the writer current pulses closer and closer together. The group at the left allows a length of 2S for each BIT, and the playback response for each pulse written in the medium appears reasonably distinct, both for the pulses repeated with like sign, above, and for the sequence of alternating sign below. The next group from the left allows one and a half S for each BIT, and the discrete character of the response to each pulse is retained in the upper wave train for repeated pulses, but is obscured in the lower oscillogram of alternating kinds of BITs. The further packing illustrated in the two remaining groups, at BIT lengths of S and three-quarters S, results in a completely changed appearance in the response to BITs of alternating kind.

So far as we know, the conventional approach to self-clocking high densities in digital recording at the time our development was done, was that of packing writing pulses (of opposite polarities for the two kinds of BITs, and no pulses in the absence of information) as close as practical in any group without losing the normal shape and visual identity of the playback response to each. Reliable reproduction was limited to densities characterized by the appearance, in Figure 4, of the left group of playback signals. In terms of our nomenclature, then, the density limit for the conventional pulse system, self-clocking, would be at about 2S per BIT, or at lambda equals 2S. Figure 5 illustrates waveforms for such a system in the top oscillograms.

Below, to the same scale in Figure 5, are the waveforms for a conventional recording with external clocking. Here both the external clock and the externally clocked information show their two necessary conditions by the absence or presence of but one polarity of writing pulse. As previously seen in Figure 4, pulses of the same polarity can be crowded closer together without losing their characteristic response shape. This advantage is used in the closer spacing realized by the externally clocked BITs in the so-called conventional pulse system below in Figure 5.

The particular sequence of 8 BITs, 0 1 0 1 0 1 1 0, used in Figure 5 for demonstrating the density limits of the conventional pulse system has, for ease of comparison, been chosen the same as the sequence illustrating our high density system in Figure 1.

That illustration is now duplicated in Figure 6, with writer currents and scale in terms of S added, for ease of direct comparison with Figure 5. With the latter still fresh in mind, let us make that comparison before getting absorbed in the characteristics and circuitry yielding response validity.

Appraisal of Figure 6 in terms of 5 reveals a BIT space of only S instead of 2S, self-clocking, and, in the same ratio, external clocking takes only one-half S instead of S.

Thus we have answered the question, "How High is High Density?", with the reply "Twice Conventional." We have yet to point out how the system works. This will involve details which differ between self and external clocking, so we shall consider these cases separately.

Self-Clocking High Density.

Figure 6 reveals that we utilized the completely changed appearance of response to alternating kinds of BITs illustrated in Figure 4 by the two most crowded groups at the right. There we held writing pulse width constant at one-half S, for optimum resolution, and observed that crowding down to a BIT space just twice this pulse width resulted in radical change in response form, but no change in peak amplitude. Further crowding to a BIT space less than twice the writer pulse width, changed amplitude without changing the number of peaks or inflections. Any reader circuit which would decipher the third group seemed likely to work on the fourth, and likewise on one with form lying between the third and second, and if so, could be said to have range with respect to density. From the trend in Figure 6, such range appears centered about the density represented in the third group, at the boundary between form and amplitude variations.

To show such range possibilities in more detail, we let the writer pulse width vary with BIT space, in the ratio found at the form-amplitude-boundary for optimum resolution pulses; pulse width equals half a BIT space. The effect is shown in Figure 7, where BIT length, lambda, takes on the values: 3S/4, S, 5S/4, and 3S/2. As BIT length is actually the quotient of velocity divided by frequency, Figure 7 illustrates the effect on playback waveform resulting from changes in either velocity or frequency of the equipment.

Because velocity and frequency are usually held constant within close limits in actual equipments, it is of more practical interest to see the effect on playback waveform when the "spread", S, is varied. We know S can vary from one transducer to another - and even in the same head with use, in the case of physical contact with the medium. So we replotted the story of Figure 7 in Figure 8 with constant BIT space, lambda, and with "spread", S, taking on different values in terms of the fixed BIT length.

The playback voltage oscillograms in Figure 8 show the differences due to variations in S. They also show similarities sufficient for more range than needed for reliability with commercial components.

Although there is apparent an end-wave-shortening, more easily seen on the starting end where it results in an obvious leftward shift of the wave trains, as S is decreased, it will be found that the actual spacing between voltage-axis-crossings is identical for corresponding waves in all four trains. Furthermore, there is a crossing at the center of the response to each and every BIT's writing pulse. There are, it is true, additional crossings at the junctions of the responses to like BITs. But if we can ignore these while recognizing the central crossings, we have the means of indexing every recorded BIT at the center of its playback response - in other words we have self-clocking.

A means for such selective recognition may be seen more clearly by reference to the playback voltage rectangular wave at the bottom of Figure 8. This wave shape, except for its shorter terminal lobes, would result from amplifying and clipping any of the actual signals above. Incidentally, had S been followed down to zero in the signals above, their end lobe length would have shrunk to that of the rectangular wave.

Now if we differentiate the rectangular wave, and rectify the resultant positive and negative voltage spikes, we have a similar spike signal at every node of the rectangular wave. Let's eliminate only the first one, as by transmitting the nodal spikes through a gate opened by an R-C delayed potential derived from rectification of the playback signal. Now our first transmitted spike is the one at the center of the first BIT's response. Suppose we use these spikes to drive an astable or one-shot multivibrator whose period is three quarters of a BIT period. The response of this multivibrator to the driving spikes will be as shown by the bottom line of Figure 8, labeled "playback clock". The multivibrator responds to every BIT center crossover, yet ignores the BIT transitional or spurious crossovers, and so fulfills the function of a playback clock.

The length of the playback terminal lobe at high density posed an interesting problem. This length may be seen to vary, with S, about a design-center value of 3/4 lambda. This, you recall, is also the design-center value for the clock's astable multivibrator period. So a spurious clock pulse can be expected to follow each proper group, or not, depending on variations from design-center value in either the clock or the end lobe. For maximum reliability the clock period should not be compromised, and at high density it is impossible materially to shorten the terminal lobe. But we are free to lengthen that terminal lobe. This we did by a circuit in the writer under control of a predetermined counter set at the number of BITs in the written group. Ambiguity in the number of detected clock pulses was thus eliminated by ensuring that the possible extra clock operation always took place. The spurious but dependable final pulse needed only to be effectively gated out. To keep the reader flexible in respect to ability to read groups of different length, without requiring control information as to group length to be written into each group and so wasting information space, the reader included a single BIT storage unit of our standard shift register, through which information was shifted as read, excepting at the first clock pulse of each group. This pulse was used to place the first read BIT in the storage unit, but not shift out its initial ambiguous content resulting from the preceeding group's extra clock pulse. The result at the reader's output was that of gating out the first rather than the last clock pulse, and correspondingly delaying the information by one BIT period. Thus the spurious terminal clock pulse is effectively gated out without knowledge of when it is coming - that is, without telling the reader the group length. It has been whispered about that we fixed the gamble on the end lobe so the self-clock with the devious manner could always win.

The full recorded information, it is found, will be reconstructed by letting the rising edge of each clock pulse, through suitable gating means, indicate the polarity of the playback signal immediately preceeding that clock pulse. This provides for simple loading of a shift register.

The rectangular wave playback voltage in Figure 8 could have been produced by a perfect transducer and medium, in which the value of S would be zero, if the recording current had varied as the rectangular wave's integral, or as the saw-tooth wave shown directly above. This saw-tooth wave is seen to be the straight-line average of the pulse-formed writing current at the top of Figure 8. Such a saw-tooth recording current would not provide the ultimate playback resolution at limiting densities, but would obviously extend the range in-

definitely downward by filling in the playback voltage valleys that are seen to creep into our high density pulse system as waveform distortion when the actual density is lowered below design-center for optimum high density.

Although, in a system specifically developed for high density, there seems little point to a modification permitting it to be used at lower densities where systems with less circuitry suffice, the saw-tooth recording current has been found convenient for use in the development, and incidentally, provides reliably for considerably higher densities than conventional systems, itself.

With respect to appearance of our self-clocking playback waveform, there is some suggestion of frequency-shift keying of an irregular and synchronously timed nature, revealing half-cycles at either frequency among cycles and half-cycles at the other, and a 2-to-1 ratio between frequencies. It seems significant that whereas the maximum frequency (resulting from repetition of like BITs) is that of BIT occurrence, the signal fundamental for alternating BIT values is actually only half the BIT frequency. Although the playback shows a continuous waveform throughout any group of recorded BITs, its quiescence immediately before and after such a group precludes reference to it in terms of such carrier modulation systems as FM, PM, or even Frequency-Shift Keying, without labored qualifications. About the best we've done for a concise definition in terms of playback waveform make-up is this: "Gated, Contiguous, Invertable Square Wave".

At any rate, with respect to the idealized playback waveform, or the rectangular wave at the bottom of Figure 8, it will be found that each BIT is indeed a square wave: 0 is represented by a square wave with its first lobe negative, and 1 by a square wave of equal size but inverted; these square waves are contiguous; and they aren't there when there is no information, hence they must have been gated.

Externally Clocked High Density.

Our high density system is much simpler in details for external than for self clocking. For example, it might well use negative and positive saturation for the two required magnetic states. In any event, it is noteworthy that every change in state, regardless of direction, is to be accepted by the reader as a signal of the same kind: as a clock pulse, in that channel; and as a 1, in the information channel.

While not demonstrated in Figure 6, where the number of BITs and also of 1's in the information group happened to be even, it is reasoned that writing current, in the clock head at the end of any odd number of BITs, or in the information head after writing an odd number of 1's, will finish at the value alternate to its starting value. The writing current merely steps, in alternate directions, but one step for each signal.

With respect to writing current, then, this is an alternate-direction, single-step system.

With respect to playback response, however, as recalled from the response shown in Figure 2 for step current, we do have a pulse system. Not

only is the voltage peak a characteristic of each signal, but voltage axis crossings are definitely not an inseparable attribute of each signal. This is apparent in the information channel where 1's happen to be separated by one or more 0's.

Correspondingly our reader, for separately clocked high density reproduction, rectifies both clock and information playback signals, and utilizes the rectified peaks: clock alone indicates a 0; clock and simultaneous information peak indicates a 1.

Common Characteristics.

The self and externally clocked versions of our high density system both resulted, perhaps, from a shift in viewpoint toward concentrating on playback waveform rather than recording current as a starting point.

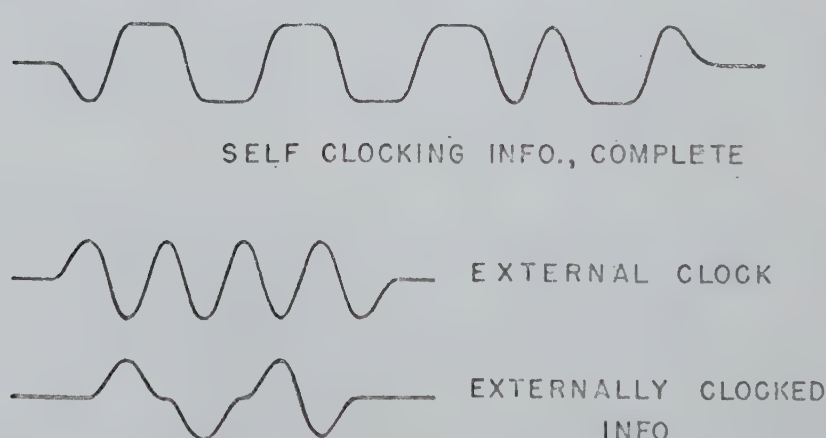
Functionally, they both shifted some of the burden of the intelligence reproduction from the magnetic storage medium to the reader circuits.

With respect to appearance of playback voltage waveforms, they both appear to have less inflection points, and less harmonics of BIT frequency, and would require less band width to transmit, than others. Possibly both may even turn out to be minimum band width, or maximum density systems - and to have been used, casually, by Edison.

Anyway they both do make good use of the excellent magnetic surfaces and reproducing heads now available.

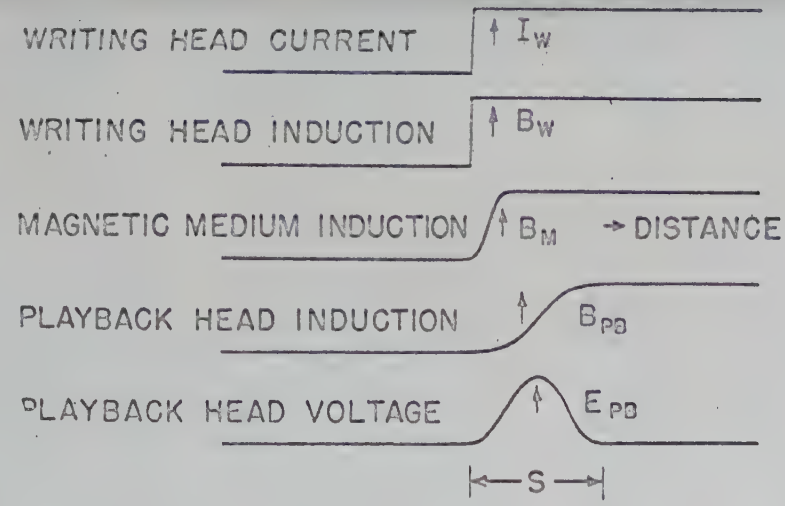
ACKNOWLEDGEMENT

Acknowledgement is gratefully made to Mr. Alfred W. Barber for valuable suggestions relative to high density digital recording.



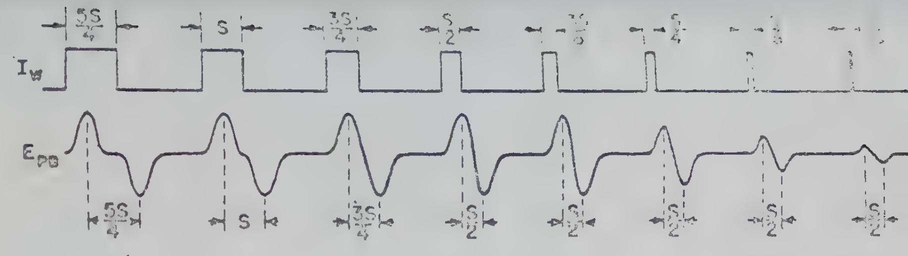
HIGH DENSITY PLAYBACK
OF 01010110

Fig. 1



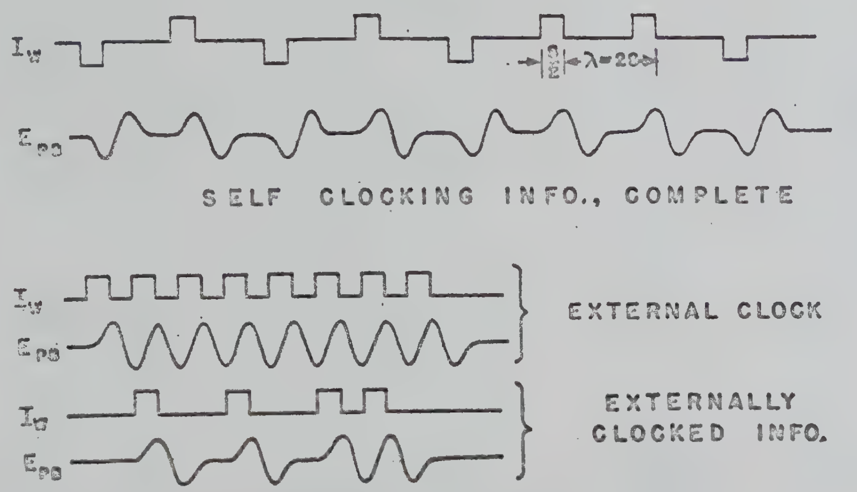
LINEAL RESOLUTION

Fig. 2



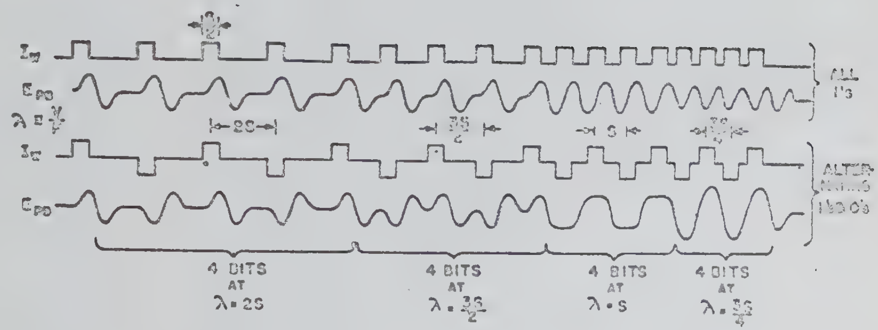
WRITING CURRENT PULSE WIDTH VARIATION EFFECTS ON THE PLAYBACK VOLTAGE WAVEFORM

Fig. 3



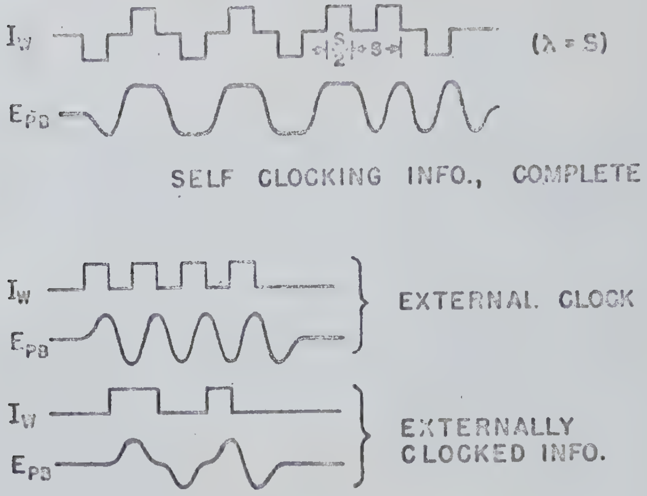
CONVENTIONAL PULSE SYSTEM, 0101011O

Fig. 4



FOUR GROUPS OF FOUR BITS EACH, AT FIXED WRITING CURRENT PULSE WIDTH = $\frac{S}{2}$ SHOWING EFFECT ON PLAYBACK VOLTAGE CAUSED BY PROGRESSIVELY SHORTENING THE PULSE INTERVAL, $\lambda \equiv$ (LENGTH OF MEDIUM ALLOWED PER BIT)

Fig. 5



HIGH DENSITY PULSE SYSTEM, 01010110

Fig. 6

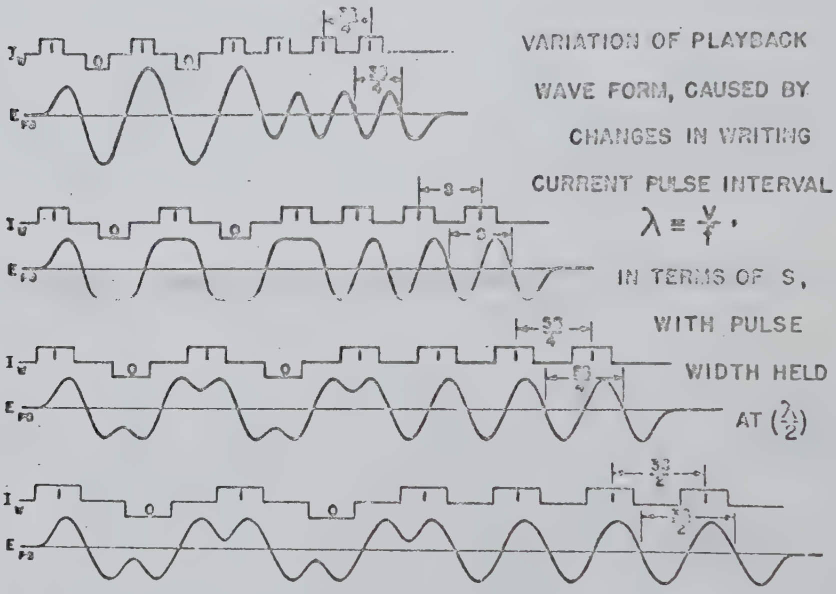


Fig. 7

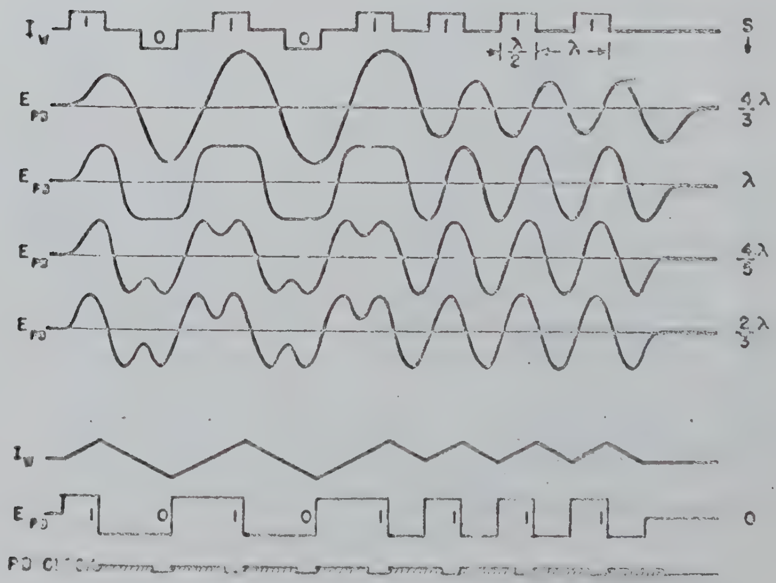


Fig. 8

A COMPUTER FOR FLAW PLOTTING

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Ultrasonic vibrations provide the only known physical means for the non-destructive examination of thick sections of dense materials. The basic method is simple; the equipment is relatively inexpensive, and there is no hazard to operating personnel. Ultrasonics will not completely supplant the older, established techniques of radiographic, magnetic, or dye inspection methods, but it will do inspection jobs which cannot be done by any of these methods. The most commonly used ultrasonic inspection method at the present time is the "contact" method, where the transducer is pressed directly against the surface of the part to be inspected. This is not a method readily adapted to mechanized scanners. The mechanized scanner proceeds in an orderly manner, and avoids the repetitive scanning generally required by the manual method to assure complete coverage.

An alternative to the "contact" method is the immersed method pioneered by D. C. Erdman[1]. In this method both the transducer and the part to be inspected are immersed in a liquid coupling bath. The transducer is not in contact with the part, but several inches away. This makes the use of mechanized scanners relatively simple, and overcomes a number of serious problems. (1) A single transducer can be used on either plane or curved surfaces. (2) A machined or ground surface is not required. (As forged, or even as cast, surfaces present no special problem.) (3) The receiver has time to recover from the initial overload caused by the transmitted pulse, so that defects near the surface may be detected.

However, there are two disadvantages. (1) There is a loss of approximately 18 decibels of signal at the interface between water and steel. (2) If the beam does not enter the part normal to the surface, it will refract at the surface to an angle at least four times the angle in water.

If the parts to be inspected are restricted to objects having a plane surface, the scanner can be very simple, and the presentation may be a cross section view through the part displayed on a cathode ray tube, similar to a radar "B" scan. This can be a very useful scanner and display, but it is not adequate for a more complex shape, such as the forging for a jet engine turbine wheel. To adequately inspect one of these wheels by a hand-operated, immersed scanner, using the usual "A" scope presentation, may require eight hours inspection time. This is generally considered to be excessive, so that only prototype inspection, or randomly selected samples are inspected. This can result in many hours of machining time being spent on a forging, only to find that the forging was defective.

A special purpose scanner was produced to perform production testing of these and similar forgings. The forging, a wheel, is mounted on a vertical axis and rotated at approximately one revolution per second. The transducer is mounted at the end of a long cantilever arm which can position the transducer under, along side, or over, the wheel. The transducer mount at the end of this

arm can rotate about an axis normal to the plane in which this arm is translated. This permits the beam to be directed so that it enters the part normal to the surface, and the ultrasound will propagate in a straight line, even though the velocity of the ultrasound in the steel is four times the velocity in water.

This scanner operates twenty or thirty times faster than an operator is able to interpret the data displayed on an "A" scope. The operator may sense the presence of a flaw, but would be unable, without stopping the machine, to describe its location and extent. Therefore, a display system of considerable refinement is required. The "B" scan is an improvement, but would yield very misleading and distorted pictures.

The display used with this scanner consists of three simultaneous views of the part; top, front, and side in an orthographic projection. As the parts are perfectly round, the selection of the "front" and the "side" is completely arbitrary, but for reference the wheel is so indexed. Each of these views is displayed on a separate projection type television cathode ray tube. Three optical systems, consisting of two front surfaced mirrors, and an objective lens each, bring the three images together on a single 3-1/4 by 4-1/4 film which is exposed during an entire inspection cycle. This picture is used both for evaluating the forging, and for a permanent record. A Polaroid-Land camera monitors one of the views so that the results, at least tentatively, can be obtained immediately. In addition to the recording camera, any of the three views can be monitored by a long persistance, directly viewed cathode ray tube.

The heart of this system is an electronic, analog computer, which links the scanner to the recording camera. The computer controls the servo operated scanner; it positions the transducer and directs it to scan at a uniform rate, referred to the surface of the part. The computer receives data from the scanner, which includes the angle of rotation of the wheel, and computes the position in space of the surfaces which reflect the ultrasound. The velocity of sound in steel, is approximately a quarter of an inch per microsecond, so that real times for this computation run less than one hundred microseconds in most cases.

Operation of the machine is automatic, and the routines involved for checking and calibrating prior to inspection, are controlled by the computer. If there is a malfunction during the check period, the computer halts the inspection and alerts the operator. If the machine is operating satisfactorily during the check period, the computer proceeds through the inspection cycle. When the inspection is complete, the computer returns the scanner to a position safe for replacing the part, and signals the operator that the inspection has been completed.

The acutal computation is performed in two distinct systems. Static, or slowly moving signals are handled in a four hundred cycle carrier system. Linear signals are represented by potentiometers, and the trigonometric equations are solved in electromagnetic resolvers. The equations solved, and the circuits used are very conventional, and do not require detailed explanation here. The position of the point where the beam enters the part is computed in a four hundred cycle system, then converted to direct current signals by phase sensitive detectors.

A basic, linear sweep is generated to represent the propagation of the ultrasound through the object under inspection. This sweep is resolved in three steps into three components, which are added to the corresponding three D.C. signals. These composite signals are transmitted to the recording camera, and to the monitor scope. This sweep is a complex waveform and is not suitable for resolving in an electromagnetic resolver. Resolvers were used during the war on some radar PPI displays, but the accuracy is not adequate for this purpose, due to poor frequency response. This is greatly aggravated by the three resolving steps being in cascade.

An electrostatic resolver is used for this function. The driving power required for this resolver is low; no transformer is required, and the frequency response is excellent. The resolver consists of an air variable capacitor with two pairs of stators, and one specially shaped rotor. Each pair of stators is driven by a balanced, push-pull amplifier and one signal is taken from the rotor. If both sine and cosine output signals are required, a pair of condensers is necessary. This is the case for each step of the computation in this computer.

The condensers which were available when this computer was built, were not designed to be resolvers, but were used in the continuously variable phase shifter in the range measuring system of an early Fire Control radar. Accuracy in that application was achieved by using a coarse and fine range measuring system. These units (Cardwell model KS-8534[2]) are undesirably large, and are not adequately shielded from either dirt or electrical interference, and the accuracy is not competitive with electromagnetic resolvers which are now available. However, experience in this laboratory with these relatively crude units leads to the conclusion, that the shortcomings are not fundamental, and that with relatively little development an electrostatic resolver would become an important component in electromechanical computing systems. Only a simple resistance-coupled amplifier is required to resolve either complex waveforms or sinusoidal signals in the frequency range of 3 cycles per second to 300 kilocycles per second.

Static signals can be resolved, if a carrier system is used. The carrier frequency can extend over the range indicated above, or conceivably, may be even higher in frequency, if a tuned amplifier is used.

The machine was delivered to the Ladish Company in Milwaukee, where it is presently being evaluated, by using it for the production inspection of forgings. Experience with the machine is not yet adequate to justify complete reliance on the automatic inspection; the results are still being correlated with those obtained by the older inspection methods.

1. Smith, Rebecca H. and Erdman, Donald C. Immersed Ultrasonic Inspection, Iron Age, August 4, 1949
2. Blackburn, John F. et al, Components Hand Book, Volume 17, Massachusetts Institute of Technology, Radiation Laboratory